Virginia Water Resources Research Center
Annual Technical Report
FY 2007

Introduction

The Virginia Water Resources Research Center (VWRRC) was established at Virginia Tech in 1965 as a federally authorized program. In 1982, the Virginia General Assembly authorized the VWRRC as a state agency under the Code of Virginia (§23−135.7:8).

Mission

The VWRRC provides research and educational opportunities to future water scientists; promotes research on practical solutions to water resources problems; and facilitates the timely transfer of water resources information to policy−and decision−makers.

Mission Elements

Research

Assisting university researchers in securing research support funds from public and private sources.

Assisting university researchers in initiating and executing water resources research.

Education

Advancing educational opportunities for students in water−resources fields by helping university researchers provide undergraduate and graduate research opportunities in water resources.

Initiating and expanding student intern opportunities with the private and public sectors.

Identifying water resources scholarship opportunities.

Outreach

Maintaining a publication series that synthesizes and reports on water resources science, engineering, and policy.

Securing academic advisors to work in an advisory capacity with the public and private sector.

Initiating and participating in the design and execution of conferences and symposia on Virginia, regional, and national water issues.

Program Administration

Administrative oversight is provided by the Dean of the College of Natural Resources. A Statewide Advisory Board appointed by the Governor advises the VWRRC director on state water research and information priorities. Because of its multiple legislative authorities and administrative responsibilities, the VWRRC has a number of reporting responsibilities. In addition to the annual reporting requirements to the USGS and the National Institutes for Water Resources (NIWR), it presents an annual report to the Virginia Tech administration. Five−year reports and reviews are presented to the USGS and the State Council on Higher Education for Virginia (SCHEV).

National Affiliations

The VWRRC is affiliated with NIWR and University Council on Water Resources (UCOWR).

Programs of the VWRRC

The programs are structured to meet the VWRRC's strategic goals and are consistent with the VWRRC mission as authorized by the U.S. Congress through the Water Resources Research Act of 1984, (Public Law 98−242) and Code of Virginia (§23−135.7:8). Programs in research and education are available to students and faculty at all Virginia colleges and universities. Outreach and collaborative programs include information transfer to policy/decision makers and citizens, and collaborative partnerships with state agencies and other water interest groups.

1) Research Programs

(a) The VWRRC's statewide competitive grants program provides research funds (up to $20,000) to find practical solutions to water problems in Virginia and the region. The grant period begins July 1 and ends June 30 of the following year. The review criteria include the technical merit of the proposed project, its relevance to Virginia and the region, its address of cutting−edge water issues, and its ability to provide research opportunities for graduate and undergraduate students. A list of water research needs in Virginia compiled from input by university researchers, state and local water agency personnel and water utility managers is available on the VWRRC website: http://www.vwrrc.vt.edu/special_reports.html.

(b) The VWRRC applies for external grants and conducts in−house research.

(c) The VWRRC facilitates team building and interdisciplinary, multi−institute collaborative research.

(d) The VWRRC facilitates research opportunities to other university faculty and external contractors through a partnership with federal agencies that provide targeted funding from the USGS.

2) Educational Programs

(a) The VWRRC provides research opportunities to undergraduate students and assistantships to graduate students who participate in sponsored research. Also, numerous graduate and undergraduate students are supported through the VWRRC's competitive grants program in Virginia Tech academic departments and at Virginia's other colleges and universities.

(b) In 1999, the VWRRC established the William R. Walker Graduate Research Fellowship to honor the many contributions of Dr. William R. Walker, the VWRRC's first director. The $2,500 award is intended for individuals preparing for a professional career in water resources. Details of the program can be found on the VWRRC website: http://www.vwrrc.vt.edu/walker_fellowship.html

(c) The VWRRC Undergraduate Research Summer Fellowship provides $2,500 scholarships to students and $500 to faculty mentors for 10−week summer internships. Recipients are selected through a statewide competition.

(d) Virginia Service Training for Environmental Progress (STEP) provides summer internships to students working in service−learning partnerships with Virginia communities on water−related issues. The competitive program accepts both undergraduate and graduate students. Recipients are selected through a statewide competition.

(e) The VWRRC coordinates the interdisciplinary Watershed Management Undergraduate Minor in collaboration with five colleges and ten departments at Virginia Tech and a Watershed Management Graduate

Certificate Program at Virginia Tech.

(f) The VWRRC supports the Virginia Tech Chapter of the American Water Resources Association.

3) Outreach and Collaborative Programs

(a) The VWRRC provides administrative support for the Virginia Water Monitoring Council.

(b) The VWRRC publishes research reports, symposia proceedings and citizen education booklets. It provides funding for the publication of outreach efforts.

(c) The VWRRC publishes a quarterly newsletter, Virginia Water Central. It features scientific and educational articles, legislative information, and news of interest. The newsletter is available to the public at http://www.vwrrc.vt.edu/watercentral.html and electronic copies are provided via email to more than 500 people.

(d) The VWRRC sponsors or co−sponsors symposia, workshops, and seminars.

(e) The VWRRC facilitates peer reviews for state programs when requested.

(f) The VWRRC website (http://www.vwrrc.vt.edu/) serves as a repository of the Center's publications, houses an academic expert database, and hosts other relevant programs.

Research Program Introduction

The research program of the VWRRC is supported through its Virginia state appropriation, external funding, and overhead generated by external funding. The 104 federal funds are not allocated to support research but are used to support the outreach and information dissemination programs of the VWRRC. During FY2007, the VWRRC funded two research projects through its competitive grant program and awarded one William R. Walker Graduate Fellowship Award. For the USGS reporting period, funding for five facilitated grants passed through USGS; projects were managed by the VWRRC. Basic information and resulting products are described in the following section.

The following publications have been produced during the reporting period based on support from state appropriations as described above.

Buchholz, T., D. Bork and T. Younos. 2007. Urban Stream Daylighting Design Application to Stroubles Creek. SR36−2007. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia. 55 pp. http://www.vwrrc.vt.edu/special_reports.html#2008.

Buchholz, T. and T. Younos. 2007. Urban Stream Daylighting: Case Study Evaluations. SR35−2007. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia. 37 pp. http://www.vwrrc.vt.edu/special_reports.html#2008.

Sullivan, C., C. Mitchelmore, R. Hale and P.A. Van Veld. 2007. Induction of CYP1A and DNA damage in the fathead minnow *(Pimelphales promeals)* following exposure to biosolids. Science of the Total Environment 384: 221−228.

Zhao, Z., K.F. Knowlton, and N.G. Love. 2007. Dairy manure estrogens with advanced treatments. J. Dairy Sci. 90(Suppl. 1): 332.

Eisenbies, M.H., M.B. Adams, W.M. Aust, J.A. Burger. 2007. Bibliography Concerning Forest Water Yields, Flooding Issues, and the Hydrologic Modeling of Extreme Flood Events. GTR−NRS−8. USDA Forest Service, Newton Square, PA. 40 pp.

Grant No. 06HQGR0021 Nutrients in Lakes and Reservoirs – Literature Review

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Congressional District:	Ninth
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Descriptors:	Lakes and reservoirs, criteria development, nutrient enrichment
Principal Investigators:	Tamim Younos

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2. Walker, Jane; Tamim Younos; Carl Zipper. 2007. Nutrients in Lakes and Reservoirs: A Literature Review for Use in Nutrient Criteria Development. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia.

VIRGINIA WATER RESOURCES RESEARCH CENTER

NUTRIENTS IN LAKES AND RESERVOIRS – A LITERATURE REVIEW FOR USE IN NUTRIENT CRITERIA DEVELOPMENT

SPECIAL REPORT

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
BLACKSBURG, VIRGINIA
2007

NUTRIENTS IN LAKES AND RESERVOIRS – A LITERATURE REVIEW FOR USE IN NUTRIENT CRITERIA DEVELOPMENT

Grant No. 06HQGR0021

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VWRRC Special Report SR34-2007

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-- Section II-D. Relationship Between Fisheries and Natural Community by John J. Ney, Department of Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University (from Zipper *et al*. 2005); and

-- Section II-E. Recreational User Perceptions of Lake/Reservoir Water Quality by Kurt Stephenson, Department of Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University (from Zipper *et al*. 2005).

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ACRONYMS AND ABBREVIATIONS

A&W: aquatic life and wildlife
AAC: Academic Advisory Committee
ac: acre
ADEQ: Arizona Department of Environmental Quality
Agg Ecor: aggregate nutrient ecoregion
$AlCl_3$: aluminum chloride
APHA: American Public Health Association
ATP: adenosine tri-phosphate
$Ca(NO_3)_2$: calcium nitrate
CDC: Centers for Disease Control
CHF: Central Hardwood Forests
Chl-*a*: chlorophyll-*a*
CO_2: carbon dioxide
d: day
DNA: deoxyribonucleic acid
DO: dissolved oxygen
DWS: domestic water source
EPA: U.S. Environmental Protection Agency
FBC: full-body contact
Fe^{2+}: ferrous ion or iron (II)
Fe^{3+}: ferric ion or iron (III)
$FeCl_3$: iron chloride
ha: hectare
HCO_3^-: hydrogen carbonate ion (bicarbonate ion)
H_2CO_3: carbonic acid
HPLC: high pressure liquid chromatography
kg/ha: kilograms per hectare
L: liter
m: meter
µg/L: micrograms per liter (1 µg/L = 0.001 mg/L = 1 ppb = 1 mg/m^3)
mg: milligrams
mg/m^3: milligrams per cubic meter (1 mg/m^3 = 0.001 mg/L = 1 ppb = 1µg/L)
mL: milliliters
mg/L: milligrams per liter (1 mg/L = 1,000 µg/L or 1,000 mg/m^3)
MPCA: Minnesota Pollution Control Agency
n: number of observations in a sample (sample size)
N: nitrogen
NC DENR: North Carolina Department of Environment and Natural Resources
NC WRRI: North Carolina Water Resources Research Institute
NGP: Northern Glaciated Plains
NH_3: ammonia
NH_4^+: ammonium ion
$(NH_2)_2CO$: urea
NLF: Northern Lakes and Forests

NMW: Northern Minnesota Wetlands
NO_2^-: nitrite ion
NO_3^-: nitrate ion
P: phosphorus
PBC: partial-body contact
PO_4^{3-}: phosphate ion
PP: Paleozoic Plateau
ppb: parts per billion (1 ppb = 0.001 mg/L = 1 μg/L = 1 mg/m^3)
r: coefficient of correlation for a sample
r^2: coefficient of determination for a sample
RRV: Red River Valley
SD: Secchi depth or Secchi disk depth
SEM: structural equation modeling
SONAR: Statement of Need and Reasonableness
TIN: total inorganic nitrogen
TKN: total Kjeldahl nitrogen
TN: total nitrogen
TP: total phosphorous
TSI: Trophic State Index
U.S. EPA: United States Environmental Protection Agency
USGS: United States Geological Survey
VDEQ: Virginia Department of Environmental Quality
WCP: Western Corn Belt Plains
WHO: World Health Organization
wt: weight

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) has identified excess nutrients as a major reason for impaired water quality in the nation's waters. The U.S. EPA is therefore directing states and authorized tribes to develop numeric criteria for nutrients to protect the designated uses from cultural eutrophication (waters enriched with nutrients because of human activities). The goal of this document is to conduct a review of literature pertinent to the dynamics of nutrients in lakes and reservoirs. The objective is to provide information for nutrient criteria developers for use in establishing scientifically defensible nutrient criteria for lakes and reservoirs. The review is separated into three main sections entitled: (1) Background Information, (2) What We Know, and (3) Toward Developing Nutrient Criteria.

BACKGROUND INFORMATION

Phosphorus and nitrogen are essential nutrients for living organisms and often limit the growth of phytoplankton and aquatic plants living in lakes and reservoirs. Furthermore, in excess supply, these nutrients have been associated with a proliferation of phytoplankton and aquatic plants that can interfere with the designated uses of lakes and reservoirs. Although an excessive supply of nutrients in lakes and reservoirs can lead to eutrophic conditions, the nutrients themselves generally do not interfere with the designated uses. Instead, it is the biological response to the nutrient enrichment that causes most of the problems. Such responses include heavy growths of phytoplankton and aquatic plants that can lead to the depletion of dissolved oxygen concentrations, fluctuations in the pH of the water, changes in the taxonomic composition and structure of aquatic communities, the release of toxins from certain phytoplankton, and disinfectant byproducts in treated drinking water.

WHAT WE KNOW

Although there are many similarities between lakes and reservoirs, this review focuses on the differences. Compared to natural lakes, reservoirs tend to be more influenced by nutrients and other substances transported from the surrounding land. Lakes and reservoirs also differ in the amount of phytoplankton and aquatic plants (primary production) that can be supported. Because of the many differences between natural lakes and reservoirs with respect to nutrients and primary production, empirical models developed from dataset for natural lakes tend not to work well in reservoirs.

Reservoirs exhibit special characteristics that are likely to affect nutrient criteria development. For example, dams can cause a longitudinal gradient from the inflow to the outflow of reservoirs. Dams also have the ability to trap large amounts of sediment, which can affect primary production by supplying nutrients to the system and/or by reducing light transmission. Internal loading of nutrients, a process whereby phosphorus is released from sediments under conditions of low oxygen, can be significant in reservoirs. Because reservoirs serve multiple purposes, developers of nutrient criteria may need to weigh the nutrient-level requirements of various uses.

The hydraulic residence time, also referred to as hydraulic retention time, refers to the rate of water movement from inflow to outflow. It is related to the morphological features of lakes and

reservoirs and impacts both physical and biological processes. Numerous studies have shown a strong relationship between hydraulic residence time and primary production, with long residence times being associated with higher abundances. Because hydraulic residence time is closely linked with primary production, lakes and reservoirs can be classified by residence time as a part of nutrient criteria development.

Fish production in lakes and reservoirs can be limited by insufficient food and/or inadequate habitat. Low nutrient concentrations can constrain food supply by limiting primary production, and high concentrations of nutrients can limit suitable habitat by causing oxygen depletions. To protect aquatic life, therefore, nutrient conditions that promote healthy fisheries need to be considered.

User perceptions of water quality conditions can be used to indicate a lake or reservoir's ability to support recreational uses. A review of the literature concerning user perceptions reflects a general theme: the level of water quality deemed suitable for swimming varies significantly between regions, lakes, and individual users. Because of this variation, no single water clarity threshold appears to be applicable for nutrient criteria development.

U.S. EPA requires that nutrient criteria protect the uses of proximal downstream waters (those within a few miles of the lake or reservoir). For natural lakes, it is generally considered that most nutrients stay trapped within the lake system. Newly constructed reservoirs tend to cause an overall gain in nutrients to downstream waters, whereas established impoundments generally reduce the annual loads of nutrients to downstream waters. The primary production of downstream receiving waters can be affected by both changes in the nutrient levels owing to the lake or reservoir and because of the addition of phytoplankton from the lake or reservoir. Furthermore, both additions and depletions of oxygen content in downstream waters have been attributed to discharges from reservoirs: discharges from deep reservoirs are likely to supply cooler, oxygenated waters, and discharges from shallow reservoirs are likely to add oxygen-depleted waters.

TOWARD DEVELOPING NUTRIENT CRITERIA

This section of the literature review provides general information about some of the most commonly considered variables for use in determining nutrient impairments. U.S. EPA recommends using a combination of both causal (*e.g.*, total phosphorus [TP], total nitrogen [TN]) and response (chlorophyll-*a* [Chl-*a*], turbidity [Secchi disk depth, SD], and dissolved oxygen [DO]) variables when developing nutrient criteria. Additionally, trophic state indices (TSIs), which describe the amount of plant biomass in a body of water, can also be used in nutrient criteria development.

Depending on the parameters utilized as nutrient criteria (*e.g.*, levels of TP, TN, and Chl-*a*), certain management practices could affect monitoring results. For example, some lakes and reservoirs used to grow fish add fertilizers that contain nutrients to encourage primary production. Other practices such as aeration to increase dissolved oxygen levels and the addition of copper sulfate to control algal blooms (practices commonly utilized in water supply lakes and

reservoirs) also need to be known before ascertaining whether or not individual lakes and reservoirs meet the developed nutrient criteria.

Across the country, various approaches for meeting EPA's nutrient criteria mandate have been proposed. This review highlights those proposed by U.S. EPA, Minnesota, Virginia, and Arizona as well as an alternative method being studied in North Carolina.

-- U.S. EPA developed ambient water quality criteria recommendations for TP, TN, Chl-*a*, and Secchi depth within each of 14 aggregate nutrient ecoregions (regions of relative homogeneity in ecological systems). For these candidate criteria, U.S. EPA used the 25th percentile from frequency distributions of data from all lakes and reservoirs within the aggregate ecoregion.

-- The Minnesota Pollution Control Agency (MPCA) is proposing ecoregion-specific nutrient criteria for its natural lakes that are based on the lake's use designation and depth. MPCA used a weight-of-evidence approach to propose summer threshold values for TP, Chl-*a*, and SD. In order for the proposed eutrophication criteria to be exceeded, both the causal variable (TP) and one of the response variables (either Chl-*a* or Secchi depth) would need to be exceeded.

-- The Virginia Department of Environmental Quality (VDEQ) worked with various researchers and stakeholders to propose ecoregional criteria. An academic advisory committee reviewed scientific literature, conducted analyses of relevant databases, and made recommendations to VDEQ. Chlorophyll-*a* and phosphorus limits were developed for 116 constructed reservoirs classified according to the type of recreational fishery supported (phosphorus applies only in reservoirs treated with algicides). VDEQ is working with other state agencies to develop a procedure to confirm use impairments based on the status of the fishery when nutrient criteria are exceeded. When the numeric criteria are exceeded but the designated uses of the water body are being attained, site-specific criteria are proposed for development. Site-specific modifications to the criteria are also proposed if the specified nutrient criteria do not protect downstream waters.

-- The Arizona Department of Environmental Quality (ADEQ) worked with a contractor to develop a "translator" approach to interpret Arizona's narrative nutrient criteria. The contractor developed a range of numeric targets for lake and reservoir water quality parameters that are expected to support various designated uses. A weight-of-evidence protocol is expected to be used to interpret the narrative nutrient criteria by systematically comparing monitoring data with the numeric targets. These targets were selected based on a review of the scientific literature, statistical analyses of water quality data from Arizona's lakes and reservoirs, and a trophic state index developed specifically for Arizona's lakes and reservoirs. Numeric targets were derived for each designated use and each lake class. Chlorophyll-*a* values were selected as the primary threshold value. Using Arizona's TSI, secondary targets were set for Secchi depth and nutrient concentrations that would be expected to maintain specific levels of Chl-*a* in Arizona's lakes and reservoirs.

-- Another method being proposed uses statistical models to predict (1) the nutrient-related parameters most likely to indicate attainment of the designated use, and (2) the criteria level that would maximize environmental protection while minimizing costs. This approach is currently (2007) being studied using lakes and reservoirs in North Carolina.

SECTION I — BACKGROUND INFORMATION

SECTION I-A. INTRODUCTION

The Clean Water Act requires states and authorized tribes to set water quality standards to protect the physical, chemical, and biological integrity of the waters within their boundaries. A water quality standard consists of three main elements: (1) designated uses, (2) water quality criteria, and (3) an antidegradation policy. Designated uses include the existing and potential uses of a water body and may differ from state to state. Common designated uses include recreational uses, aquatic life support, production of edible and marketable fish and shellfish, and supply of potable water. Criteria are set to protect the uses of the water body and can be narrative or numeric in nature. Antidegradation policies are designed to prevent the water quality from being reduced from a higher status to a lower status (U.S. EPA 2002).

The U.S. Environmental Protection Agency (EPA) has identified excess nutrients as a major reason for impaired water quality in the nation's waters. According to the U.S. EPA's *National Water Quality Inventory 2000 Report*, "more lake acres are affected by nutrients than any other pollutant or stressor…. States reported that excess nutrients pollute 3.8 million lake acres (which equals 22% of the assessed lake acres and 50% of the impaired lake acres)" (U.S. EPA 2002, page 20). Excessive nutrients in lakes and reservoirs can lead to blooms of algae, overabundance of aquatic plants, low dissolved oxygen levels, fish kills, and species shifts of flora and/or fauna. Over enrichment of nutrients may also pose human health risks through the development of harmful algal blooms (U.S. EPA 2002).

The U.S. EPA is therefore directing states and authorized tribes to develop numeric criteria for nutrients to protect the designated uses of the nation's waters. The purpose of numeric nutrient criteria is to address cultural eutrophication (waters enriched with nutrients because of human activities). Presently, all states have narrative criteria related to nutrients (U.S. EPA 2003a). Examples of narrative criteria include:

Indiana — All waters shall be free from substances "… that will cause or contribute to the growth of aquatic plants or algae to such degree as to create a nuisance, be unsightly or deleterious or be harmful to human, animal, plant, or aquatic life or otherwise impair the designated uses" (327 IAC 2-1-6).

New Mexico — "Plant nutrients from other than natural causes shall not be present in concentrations which will produce undesirable aquatic life or result in a dominance of nuisance species in surface waters of the state" (20 NMAC 6.4.12).

Numeric criteria provide specific values to measurable parameters. Relatively few states have water quality numeric criteria related to nutrients. North Carolina and Illinois are two states that have numeric criteria applicable to freshwater lakes and reservoirs to protect against nutrient impairments:

North Carolina—"Chlorophyll a (corrected): not greater than 40 µg/L for lakes, reservoirs, and other waters subject to growths of macroscopic or microscopic vegetation not designated as trout waters, and not greater than 15 µg/L for lakes, reservoirs, and other waters subject to growths of macroscopic or microscopic

vegetation designated as trout waters (not applicable to lakes and reservoirs less than 10 acres in surface area)…" (15A NCAC 02B.0211).

Illinois—"Phosphorus as P shall not exceed 0.05 mg/l in any reservoir or lake with a surface area of 8.1 hectares (20 acres) or more…" (35 Ill. Admin. Code 302.205).

To assist water quality managers in developing numeric criteria for lakes and reservoirs, U.S. EPA developed a technical guidance, *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (U.S. EPA 2000a). The U.S. EPA also proposed a set of guidance criteria for lakes and reservoirs in each aggregate nutrient ecoregion within the conterminous U.S. (U.S. EPA 2000b-h, U.S. EPA 2001a-e). These criteria are based on two causal variables (total nitrogen [TN] and total phosphorus [TP]) and two early indicator response variables (chlorophyll-*a* [Chl-*a*] and turbidity [Secchi depth]) (U.S. EPA 2000a). The ecoregion criteria proposed by the U.S. EPA are to be used as the default standard unless states and authorized tribes develop their own acceptable standards. The standards developed by states and authorized tribes must meet the following basic requirements (U.S. EPA 2000a):

- Protect the designated uses of lakes and reservoirs
- Protect the designated uses of the downstream receiving waters
- Use a scientifically defensible approach
- Use parameters that can measure the cause of and response to nutrient overenrichment.

Reckhow *et al.* (2005) suggest that states should develop criteria that are easily measured, good predictors of the designated use attainment, and consider societal values that balance environmental protection and cost. Reckhow *et al.* (2005, p. 2918) caution: "…natural variability and criterion-use prediction uncertainty will almost certainly result in some risk of nonattainment…. Furthermore, the selection of the acceptable probability [of nonattainment] is a value judgment best left to policy makers and should not be 'hard-wired' into the criteria level analysis."

1. Purpose

The goal of this document is to conduct a review of literature pertinent to the dynamics of nutrients in lakes and reservoirs. The objective is to provide information for nutrient criteria developers for use in establishing scientifically defensible nutrient criteria for lakes and reservoirs. Section I of this literature review covers background information about lakes and reservoirs, nitrogen, phosphorus, primary production, and the effects of excess nutrients and primary production in lakes and reservoirs. Section II provides an overview of nutrient-related effects on the trophic state of lakes and reservoirs. It includes a summary of the differences between natural lakes and impounded waters, the effect of residence time, and the relationship between fisheries and nutrient concentrations. This section also describes the possible downstream effects of lakes and reservoirs on other water bodies, such as downstream reservoirs and rivers. Section III of the review provides information toward developing nutrient criteria. It covers possible ways to express nutrient criteria and describes various approaches proposed for developing nutrient criteria.

2. Characteristics of Lakes

In general terms, lakes are thought of as inland bodies of standing water located within a depression of the land surface. In the U.S. EPA nutrient criteria guidance document, lakes are given a more specific definition: "Natural and artificial impoundments with a surface area greater than 10 acres and a mean water residence time of 14 or more days." Many of the natural lakes in the U.S. were formed by glaciers and are thus located in the northern latitudes. Other natural lakes common to the U.S. were formed from the dissolution of limestone, such as found in Florida and other regions with limestone bedrock (Walker 1981 in Kennedy and Walker 1990).

Water enters lakes from precipitation, runoff from the surrounding land, entering streams, and groundwater. Runoff that enters lakes first passes through the surrounding wetlands, which slows the water velocity and removes sediments, nutrients, and pollutants (Ford 1990). Lakes can lose water to the atmosphere from the surface, to downstream receiving waters from an outlet, and to the groundwater through seepage from the lake bottom.

Lake waters respond to climatic seasonal changes. For example, changes in the characteristics of lake waters occur with seasonal fluctuations of temperature and solar radiation, particularly in regard to the mixing of the upper and lower lake waters. When air temperatures and solar radiation are high, as in summer, the water in the upper part of a lake is likely to be warmer and therefore less dense than that in the lower reaches. The resulting change in water temperature with depth leads to stratified layers of water — the warmer, less dense water resides on top of the cooler, denser water. Because of the differences in the density of the water, little exchange occurs between these layers (Smith 1986). As the season changes and air temperatures cool, the upper layer also cools and become denser, similar to the lower water. Because of the similar density throughout, wind blowing across the lake is able to set up a mixing of the water column in a process known as *turnover* (Wetzel 2001).

The stratification/mixing process varies among lakes. Some examples of different ways that lakes respond to seasonal temperature changes are illustrated below:

- At spring or fall turnover, small lakes may circulate during several days of windy conditions, whereas large lakes can take several weeks to circulate (Wetzel 2001).
- Shallow lakes may mix daily throughout the year or every few days. If stratification occurs in these lakes, it generally only lasts for a week or two (Horne and Goldman 1994).
- Many temperate lakes of moderate depth that are covered by ice in winter (*e.g.*, Lake Mendota, Wisconsin) mix in the fall and spring. Ice cover prevents the wind from mixing the water in winter. Stratification thus occurs in the summer and winter (Horne and Goldman 1994, Brönmark and Hansson 2005).
- Moderately deep to deep lakes in cooler climates that are not covered by ice in winter (*e.g.*, Great Lakes, Lake Tahoe in California) may have one long mixing period that lasts from fall into the following spring/early summer and a stratification period during summer (Horne and Goldman 1994, Brönmark and Hansson 2005).

Stratified lakes can be divided into three layers of water: *epilimnion*, *metalimnion*, and *hypolimnion*. The upper layer of water is referred to as the epilimnion, and the lower layer is called the hypolimnion. The section between these two layers is known as the metalimnion. A thermocline, a region where the temperature changes rapidly with depth, separates the upper and lower layers (For temperate lakes, the thermocline is defined as the region where temperature changes are greater than $1^{o}C$ per meter depth). Because the thermocline and metalimnion occur in the same region, the terms are often used interchangeably (Horne and Goldman 1994, Wetzel 2001).

The characteristics of lake water differ between stratified layers. Because the epilimnion is exposed to the sunlight, it typically has the highest temperatures during summer and is the region where most photosynthesis occurs. Oxygen levels are frequently greatest in the epilimnion because oxygen from the atmosphere is transferred to the water and because oxygen is produced from photosynthesizing lake algae. As algal populations grow, the nutrient concentrations in the epilimnion may become depleted during the growing season. In contrast, the hypolimnion receives less light so that photosynthesis is generally not possible and the temperature remains cold throughout the year. The hypolimnion tends to have low levels of oxygen, in part, because it is isolated from the atmosphere, lacks vegetation and algae that give off oxygen during photosynthesis, and has an increased population of decomposing bacteria that require oxygen. Nutrient levels tend to be higher in the hypolimnion because deceased organisms fall to the bottom of the lake where they are decomposed and because mineral particles (*e.g.*, from soil in the drainage basin) have nutrients attached to them and accumulate at the bottom of the lake (Smith 1986).

As temperatures cool, fall turnover occurs, and the stratified layers mix, *i.e.*, the water from the upper layer mixes with the water from the bottom layer. As a result of the mixing, depleted nutrient levels in the epilimnion are typically recharged from nutrients in the bottom reaches. Likewise, depleted oxygen levels in the hypolimnion are restored by increased oxygen levels from the surface waters (Smith 1986, Horne and Goldman 1994, Wetzel 2001).

Lakes can also be described as having different zones. The littoral zone is closest to the shore. In this shallow water zone, the sunlight is able to reach to the bottom of the lake. The photosynthetic activity of this region is dominated by rooted plants such as water lilies, rushes, and cattails. The pelagic (or limnetic zone) is in the deeper, open water where light is sufficient for photosynthesis. Floating algae and cyanobacteria (formerly referred to as blue-green algae) provide the most photosynthetic activity in the pelagic zone. Below the pelagic zone, lies the profundal zone. This region of the lake is characterized by low light levels so that photosynthesis does not occur in this zone (Smith 1986, Wetzel 2001).

3. Characteristics of Reservoirs

U.S. EPA defines reservoirs as "man-made lakes for which the primary purpose of the impoundment is other than recreation (*e.g.*, boating, swimming) or fishing, and the water retention time and water body depth and volume vary widely" (U.S. EPA 2000a, p. 3-1). Hutchinson (1957) classified reservoirs as one of seventy-six lake types based on the origin of lake formation. He considered the dam as the distinguishing characteristic of reservoirs.

Reservoirs can be classified using a combination of (1) the location in the basin, (2) the operation of the dam, and (3) the hydraulic residence time (rate of water movement from the inflow to the outflow). Three types of reservoirs include: tributary-storage reservoirs, run-of-the-river reservoirs, and mainstem-storage reservoirs (Søballe *et al*. 1992, Kennedy 2001).

- Tributary-storage reservoirs, as the name implies, are constructed by holding back the waters of a few low-order rivers. Thus, tributary-storage reservoirs are generally located in upstream regions of the basin. These reservoirs are typically deep and thus able to stratify. Because tributary-storage reservoirs are often used for flood control, the hydraulic residence time can be long and quite variable (depending on the amount and timing of water input to the reservoir from precipitation or snow melt).
- Run-of-the-river reservoirs are usually located further downstream in the basin than are tributary-storage reservoirs. These reservoirs are constructed to include the original river channel and the land adjacent to the original river channel. They are primarily used for power generation or navigation. Common characteristics of run-of-the river reservoirs include high amounts of turbidity and suspended sediments. When used for power generation, the surface elevations can change daily. When used primarily for navigation, there is little change in the water depth. Run-of-the-river reservoirs tend to have short hydraulic residence times.
- Mainstem-storage reservoirs are located in downstream regions of the basin. These reservoirs are constructed by flooding broad river floodplains. Mainstem-reservoirs are often designed for controlling flood events, and/or generating power. The hydraulic residence times of this class of reservoirs vary greatly. Some offer large storage volumes so have the potential to have long residence times (Søballe *et al*. 1992, Kennedy 2001).

Reservoirs are primarily constructed in regions where there are few natural lakes. States that were not glaciated tend to have reservoirs, whereas states that were glaciated have many natural lakes so have only a few reservoirs. Thus, most reservoirs in the U.S. are located throughout the southeast, central states, southwest, and west (Thornton 1990a).

Reservoirs were built on rivers to meet a particular societal purpose or purposes. Reservoirs are primarily constructed for flood control, water supply, hydropower generation, or irrigation (Thornton 1990a). They are designed to hold back water and release it in a controlled manner. Depending on the height of the dam and the control of the outgoing flow, water storage can be short (1 day) or long (750+ days) (Kennedy 2001). Because reservoirs are formed from rivers but also store water, their characteristics are typically intermediate to those of rivers and natural lakes. Furthermore, reservoirs that more closely resemble natural lakes function within the ecosystem in a manner similar to natural lakes, whereas reservoirs that more closely resemble rivers in their physical and chemical characteristics function more like rivers (Wetzel 1990).

Like natural lakes, the water quality of reservoirs is influenced by the geology of the watershed, climate of the region, and land use within the watershed. Reservoirs receive water input from precipitation, runoff from surrounding land, and groundwater. Unlike lakes, however, reservoirs receive the major portion of inflow from a few contributing tributaries (Ford 1990, Thornton 1990b). Reservoirs can lose water to the atmosphere from the surface, to the groundwater through seepage from the basin bottom, and to downstream receiving waters from the controlled

outlet (*i.e*., the dam). Depending on the design of the dam, the outlet can be located near the surface, near the bottom, or somewhere in between. Some dams have multiple depths from which the water can be released. Reservoirs that release water from the top more closely resemble natural lakes in this attribute (Ford 1990).

Given the required climatic and morphological conditions, reservoirs are able stratify in a manner similar to lakes (*i.e*., they develop an epilimnion, metalimnion, and hypolimnion). Likewise, reservoirs can have periods of turnover. Just like lakes, reservoirs also have a littoral zone, pelagic zone, and profundal zone. Compared to natural lakes, however, reservoirs are more complex systems. For example, because of the significant flow of water from tributaries and the slowing of this water by the dam, reservoirs have a longitudinal gradient (from the region of inflow to the dam) that is lacking in lakes (see Section II-B).

4. Trophic State

Trophic state refers to the amount of plant biomass in a body of water (Carlson and Simpson 1996). Lakes and reservoirs with low amounts of plant biomass (primary production) are said to be *oligotrophic*. Those with a medium amount of production are described as *mesotrophic*, and those with high amounts of plant biomass are called *eutrophic*. *Eutrophication*, therefore, is a process whereby water bodies move from a state of lower production (*e.g.*, an oligotrophic state) to higher production (*e.g.*, a eutrophic state). Eutrophication is a natural process that eventually transforms lakes into marshes. Under natural conditions, this process can take up to millions of years for some particularly deep lakes (Horne and Goldman 1994).

The characteristics of the drainage basin (*e.g.*, amount of nutrients available to the lake system) and the mean depth of the lake or reservoir are the primary factors controlling eutrophication (Horne and Goldman 1994). Thus, activities that increase the amount of nutrients in the runoff from the drainage basin accelerate the eutrophication process. A trophic state that might take several hundred years to be reached without the influence of human settlement could be attained in decades with contributions of nutrients from human activities. This accelerated eutrophication because of human-related inputs of nutrients is called *cultural eutrophication*. Human activities that contribute to cultural eutrophication by increasing the amount of nutrients available to the lake or reservoir include discharging municipal sewage into the water body, allowing wastes from livestock and pets to enter the water body, and fertilizing cropland and lawns in the drainage basin.

Because the depth of the lake or reservoir influences the eutrophication process, the epilimnion:hypolimnion (E:H) ratio has been used as a first approximation of trophic state. This ratio reflects the volume between the zone where most algal production takes place (epilimnion) and the zone where decomposition processes are dominant (hypolimnion). If the E:H ratio is high, a more productive trophic state may be anticipated for a given nutrient load than if the ratio is low. Figure I-1, reproduced from Cole (1994) and prepared using data from Rawson (1955), illustrates the relationship between planktonic production and mean depth in lakes. The figure supports a "rule of thumb" that, absent unusual anthropogenic nutrient sources, deep lakes are generally less productive than shallow ones, and that the boundary for oligotrophic systems is a mean depth of about 18 meters (from Zipper *et al*. 2004).

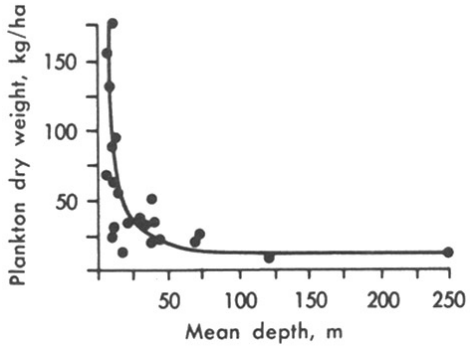

Figure I-1. Standing crops of plankton in kilograms per hectare plotted against mean depths in various lakes (Data from Rawson, 1955). Reprinted by permission of Waveland Press, Inc. from Gerald A. Cole, *Textbook of Limnology*, 4th edition. (Long Grove, IL; Waveland Press, Inc., [reissued 1994]). All rights reserved.

Horne and Goldman (1994) summarize the contrasts between oligotrophic and eutrophic lakes. In general, oligotrophic lakes have low levels of primary production and other aquatic life. They are often deep and located in small drainage basins. Oligotrophic lakes are usually lacking in at least one macronutrient, have high dissolved oxygen concentrations, and are clear. In contrast, eutrophic lakes have high levels of primary production and aquatic life. They tend to be shallow and situated in large drainage basins. These eutrophic lakes generally have high nutrient concentrations, variable oxygen levels, and low light transparency (Horne and Goldman 1994).

SECTION I-B. NUTRIENT INPUT AND FATE IN LAKES AND RESERVOIRS

Nutrients are elements used by living organisms as nourishment. Some nutrients, such as carbon (C), nitrogen (N), and phosphorus (P), are needed in relatively large supply (referred to as macronutrients) whereas other nutrients, such as iron, zinc, and copper are needed in comparatively small supply (referred to as micronutrients) (Hecky and Kilham 1988). Sources of nutrients to lakes and reservoirs include the bedrock, atmospheric deposition, vegetation and animal life in and around the water body, and input from human activities.

Primary producers, organisms able to photosynthesize, are able to absorb and use nutrients dissolved in water, whereas macroinvertebrates, fish, and other animals cannot. Thus, primary producers serve as the basis for aquatic food chains. Because phosphorus and nitrogen often limit the amount of growth by primary producers, these nutrients are sometimes referred to as "limiting nutrients." Likewise, phosphorus and nitrogen are also considered to be "causal variables" because in excessive amounts, they may cause proliferation of primary producers. For these reasons, much attention is paid to phosphorus and nitrogen when developing nutrient criteria (U.S. EPA 2000a).

1. Phosphorus

Phosphorus (P) is an essential nutrient for living organisms. For instance, phosphorus is found in DNA (the genetic material of living organisms), used to form cell membranes, and is utilized at the cell level (as ATP, adenosine tri-phosphate) to generate energy.

Phosphorus enters lakes and reservoirs from a number of different sources, *e.g.*, point-source discharges, terrestrial runoff, feces from waterfowl, decaying organisms, and rocks containing phosphorus. Some sources of phosphorus to lakes and reservoirs are natural, such as waste products from aquatic organisms and wildlife, and decaying tissues of plants and animals. Other natural sources of phosphorus in lakes and reservoirs include dissolved minerals containing phosphorus and atmospheric deposition of particulate-bound phosphorus (*e.g.*, phosphorus attached to wind blown soils). Sources of phosphorus in lakes and reservoirs that result from human activities often include industrial and municipal effluents and surface runoff from lands affected by fertilizer, poultry litter, and/or livestock waste. Human activities that increase soil erosion may also contribute phosphorus to lakes and reservoirs as particulate-bound phosphorus (Wetzel 2001, Brönmark and Hansson 2005).

In the aquatic ecosystem, phosphorus can be found in the water column, within the bodies of aquatic organisms, or attached to particles (such as in sediment) in the water. Primary producers are able to directly incorporate inorganic forms of phosphates. Primary producers may also be able to indirectly obtain phosphorus from various organic compounds (phosphorus bound to carbon-based molecules, as in excrement and in decaying plant and animal matter). For example, organic phosphorus incorporated in plant and animal tissues may be made available for use by primary producers through bacterial conversion into soluble inorganic phosphates. Likewise, particulate-bound phosphates (phosphates bound to particles) can be used by primary producers if the phosphorus disassociates from its particle to become soluble in the water column (Wetzel 2001, Brönmark and Hansson 2005).

Phosphorus can cycle for quite some time through lake and reservoir systems. It is transferred from one organism to another through food chains. Alternatively, phosphorus can sink to the bottom sediment as a part of fecal waste, a dead organism, or attached to a sinking particle. Once at the bottom of the lake or reservoir, phosphorus may become buried and unavailable to the system. Alternatively, rooted plants can transport phosphorus from the sediment into their tissues, where upon death, the phosphorus can be released back into the water (Horne and Goldman 1994). Phosphorus in sediment may be released back into the system through chemical reactions, *e.g.*, at pH values above 8, phosphate may disassociate from its particle and become soluble in water. Bottom-feeding fish and organisms that inhabit the bottom sediments such as worms and other aquatic organisms can also disturb the sediment, releasing phosphorus back into the water column. Phosphorus is released from lakes and reservoirs through the outflow to downstream waters (Hutchinson 1957, Brönmark and Hansson 2005).

Phosphorus levels in water samples collected from lakes and reservoirs are usually reported as ppb, µg/L (1 µg/L = 1 ppb), or mg/L of total phosphorus. For more information about using phosphorus as a variable for determining nutrient-impaired waters see Section III-A in this literature review.

2. Nitrogen

Nitrogen (N) is an essential nutrient for living organisms. It is primarily used to form proteins, which are the building blocks of all living matter. Proteins provide structural support, act as enzymes, regulate cell activity, *etc.* Nitrogen is also an important component of chlorophyll, the green pigment that makes photosynthesis possible.

Nitrogen in lakes and reservoirs may come from natural sources, such as the decomposition of plants and animals, waste products from aquatic life within the water, urine and feces of wildlife in the catchment, or (in generally small amounts) mineral dissolution of rocks. Nitrogen that enters lakes and reservoirs is often of direct human origin (such as discharges from sewage treatment plants or leachate from septic systems) or is related to human activities (such as wastes from poultry and livestock facilities, runoff of fertilizers, or nitrous oxides from fuel combustion). Nitrogen can be transported to lakes and reservoirs through atmospheric deposition (precipitation on the lake surface), runoff, or groundwater (Hutchinson 1957, Wetzel 2001).

Nitrogen exists in fresh water in a number of different forms. Most algae and other primary producers are able to utilize inorganic forms of nitrogen: nitrates (NO_3^-), nitrites (NO_2^-), ammonia (NH_3), and ammonium ions (NH_4^+) (Smith 1986). Some species of cyanobacteria are also able to use nitrogen (N_2) directly from the atmosphere. Various forms of organic nitrogen (nitrogen that is bound to carbon-based molecules) may also become available to algae. For example, urea ($[NH_2]_2CO$), a soluble organic compound containing nitrogen that is excreted in urine and applied to land as fertilizer, easily degrades into inorganic forms of nitrogen. Likewise, organic nitrogen found in plant and animal tissues can become available for use by primary producers if converted by bacteria into inorganic forms of nitrogen (Wetzel 2001).

Nitrogen is primarily lost from lakes and reservoirs through the outflow, in an exchange with groundwater, in the sediments, and by bacterial denitrification (*e.g.*, converting NO_3^- to N_2) with subsequent loss of nitrogen gas (N_2) to the atmosphere (Hutchinson 1957, Wetzel 2001).

Measurements of nitrogen in water samples collected from lakes and reservoirs are usually reported as mg/L of total nitrogen (TN). For more information about using nitrogen concentrations as a monitoring parameter for determining nutrient-impaired waters see Section III-A.

3. Nutrient Limitation

According to the Law of the Minimum, the growth rate of an algal cell is only limited by one factor at any given time. The limiting factor can be a nutrient, light, temperature, *etc.* Although different species have different requirements, as a generalization, plant tissue requires phosphorus, nitrogen, and carbon in the following ratio: 1 P : 7 N : 40 C by mass. This N:P ratio of 7 by mass is referred to as the Redfield Ratio, named for the oceanographer Alfred Redfield who first published it (Redfield 1934). Thus based on the nutrient requirements for P, N, and C, phosphorus is most likely to limit growth, and nitrogen is next likely to limit growth. Other elements, such as silicon, calcium, or iron, can be limiting but are not required in as large of

quantities as phosphorus, nitrogen, and carbon (Wetzel 2001). For example, because diatoms need silica in the building of their cell walls, this nutrient sometimes limits the growth of diatoms.

In 1974, Schindler published a paper illustrating P-limitation in a lake in Ontario, Canada. In his research, lake 226 was partitioned into two basins. To one basin, Schindler added nitrogen and carbon. No blooms of algae appeared in this basin throughout the year-long study. To the other basin, Schindler added equivalent amounts of N and C and also added P. A dense bloom of algae formed in the basin in which phosphorus was added (Figure I-2) (Schindler 1974).

Figure I-2. Lake 226, demonstrating the vital role of phosphorus in eutrophication. The far basin, fertilized with phosphorus, nitrogen, and carbon, was covered by an algal bloom within 2 months. No increases in algae or species changes were observed in the near basin, which received similar quantities of nitrogen and carbon but no phosphorus (Schindler 1974; photo from: Fisheries and Oceans Canada, Experimental Lakes Area [http://www.umanitoba.ca/institutes/fisheries/]).

Numerous studies since Schindler's 1974 paper have found strong relationships between TP concentrations in lakes and algal biomass (or its surrogate, chlorophyll-*a* concentrations) (Schindler 1977, Schindler 1978, Canfield and Bachmann 1981, Smith and Shapiro 1981, Canfield 1983, McCauley *et al.* 1989, Correll 1998). For example, in a study of 19 northern lakes, Dillon and Rigler (1974) demonstrated a strong linear relationship between water column TP concentration at spring turnover and summer chlorophyll-*a* concentrations ($r \sim 0.9$). Working with a data set of approximately 75 lakes from North America and Europe, Schindler (1978) found a significant correlation of annual phosphorus loading to both annual phytoplankton production and mean annual chlorophyll levels provided that a simple correction for water renewal was applied. Similarly, Rast *et al.* (1983) observed decreasing chlorophyll levels in 10 lakes that experienced phosphorus-loading declines (from Zipper *et al.* 2004).

The forms of algal responses to nutrient enrichment at relatively low levels are generally modeled as linear or log-linear functions. In studies that include lakes with very high nutrient levels, several investigators have found the relationship of TP and chlorophyll-*a* to be sigmoid (McCauley *et al.* 1989, Prairie *et al.* 1989). Algal response to TP is reduced at higher concentrations. Such a response would be expected at high phosphorus concentrations because other factors necessary for photosynthesis (other nutrients, sunlight, *etc.*) are more likely to become limiting (from Zipper *et al.* 2004).

Algae have developed a number of ways to overcome low phosphorus concentrations in water. For example, most algae are able to take in more phosphorus than needed during times when phosphorus levels are high and store it for later use when phosphorus levels in the water column are low. This process is referred to as *luxury consumption*. In addition, certain species of algae are capable of obtaining phosphorus from the water column even when the phosphorus concentration is low. A third method involves the production of phosphatase, an enzyme that cleaves the bond between phosphate and an organic particle to which it is attached. Algae able to produce phosphatase are therefore able to free phosphate from organic matter, transforming the phosphorus from an unavailable form to an available form.

Many studies have found that TN concentrations, as well as TP, (or, in an alternative formulate, N:P ratio) also influence algal responses (Smith 1982, Canfield 1983, Smith 1983, McCauley *et al.* 1989, Prairie *et al.* 1989) (Table I-1). Morris and Lewis (1986) found declines of TN to levels indicating nitrogen limitation during the midsummer months in three of eight Colorado lakes they were studying. Several studies have shown that short-term nitrogen limitations commonly occur in systems where seasonal means give no indication of nitrogen limitation (Barica 1990, Matthews *et al.* 2002). Patchy distributions of algal species and nutrients in aquatic systems, especially when stratified, can cause nitrogen limitations to occur within microenvironments even when the system average nutrient concentrations do not indicate such condition (Hyenstrand *et al.* 1998). Because some cyanobacteria are capable of fixing atmospheric nitrogen, long-term nitrogen limitation only occurs in systems with certain conditions such as micronutrient deficiencies that inhibit the growth of N-fixers (from Zipper *et al*. 2004).

More often, algal communities are co-limited by both nitrogen and phosphorus (Matthews *et al.* 2002). Co-limitation occurs because numerous species are present and because algal communities and species vary in the proportions in which they require nitrogen and phosphorus. At a given N:P ratio in the co-limitation range, some species may be limited by nitrogen and others by phosphorus (Suttle and Harrison 1988, Dodds *et al.* 1989). When algal populations are co-limited by nitrogen and phosphorus, populations can be expected to respond to changes in the supply of either nutrient (from Zipper *et al*. 2004).

A number of researchers have found that co-limitation of primary productivity by nitrogen and phosphorus is common in lakes. As reported by Dodds *et al.* (1989), "statements that phosphorous is the major nutrient controlling primary productivity in freshwater systems … should not be taken to mean that phosphorous is the only nutrient limiting productivity in all systems." An example of co-limitation is presented by these researchers. They fertilized algal cultures withdrawn from a Montana reservoir with NH_4^+ and PO_4^{3-} in proportions equivalent to

the "Redfield Ratio" and with equivalent amounts of NH_4^+ and PO_4^{3-} alone. The NH_4^+ addition alone stimulated production by 22%; the PO_4^{3-} addition increased production by 18%; and the combined addition boosted production by 40% (Dodds *et al.* 1989) (from Zipper *et al*. 2004).

In reviewing published studies of whole-lake fertilization experiments, Elser *et al.* (1990) found that enrichment by nitrogen and phosphorus, in combination, was often required to enhance algal growth and conclude that their results provide little support for the conventional wisdom that lake communities are almost always limited solely by phosphorus. A number of studies analyzing data from multiple lakes have found that regressions using both TN and TP can explain more variance in epilimnetic algae (or algal indicators such as chlorophyll) than do regressions using TP alone (Smith 1982, Canfield 1983, McCauley *et al.* 1989, Prairie *et al*. 1989) (from Zipper *et al*. 2004).

Table I-1. Nutrient ratios (as total nitrogen and total phosphorus, by mass) and concentrations cited by various sources influencing algal mass and species composition (Source: Zipper *et al*. 2004).

Ratio or Level	Significance	Study
N/P = 7	"Redfield Ratio"	
4 < N/P < 23	Range of algal cellular N/P ratios	Suttle and Harrison, 1988.
N/P < 5	Indicator of N limitation	Matthews *et al.* 2002
N/P < 10	Indicator of N limitation (ratio applied to inflow waters)	Flett *et al.* 1980 Hellstrom 1996
5 < N/P < 20	Indicator of co-limitation by N and P	Matthews *et al.* 2002
N/P = 10 to 15	Equilibrium N/P in systems where N fixers develop in response to N limitations	Hellstrom 1996
N/P > 22	At N/P ratios above 22, blue-green algal blooms seldom occur. Risk of bloom is increased below N/P = 22.	Smith *et al*. 1995
Total inorganic N < 0.1 mg/L	Indicator of N limitation	Gophen *et al*. 1999
TP < 30 μg/L	Risk of cyanobacterial dominance < 10%	Downing *et al*. 2001
TP = 30 – 70 μg/L	Risk of cyanobacterial dominance ~ 40%	Downing *et al*. 2001
TP ~100 μg/L	Risk of cyanobacterial dominance ~ 80%	Downing *et al*. 2001

4. Primary Production in Lakes and Reservoirs

Primary production refers to the amount of organic matter made from inorganic materials through the process of photosynthesis. *Primary producers* are organisms able to use inorganic nutrients through the process of photosynthesis to build organic matter. Thus, primary producers need essential nutrients — nitrogen, phosphorus, magnesium, calcium, iron, zinc, *etc.* — in sufficient amounts in order to live and grow. The main types of primary producers in lakes and reservoirs are phytoplankton, macrophytes, and periphyton.

- Phytoplankton are suspended in the water column and are made up of photosynthesizing organisms such as algae and cyanobacteria. Phytoplankton may exist as single cells, filaments, or colonies of cells. Most phytoplankton have limited mobility so are carried with the flow of the water or settle to the lake bottom. Phytoplankton tend to be the dominant algal community in deeper waters (in the pelagic zone), where the amount of sunlight reaching the lake bottom is inadequate for the growth of macrophytes and periphyton.

- Macrophytes are plants large enough to be seen with the naked eye. They generally have roots, stems, and leaves. Although mosses lack these tissues, they are also macrophytes. Macrophytes may be rooted in the sediment or free-floating. They are found near shore (in the littoral zone).

- Periphyton refers to a community of organisms usually dominated by algae but also including bacteria, fungi, protozoa, and other microbes. The primary types of algae that make up periphyton include diatoms, green algae, red algae, chrysophytes, and xanthophytes. Periphyton assemblages, also known as benthic algae, grow on stable surfaces, such as rocks, woody debris, and vascular plants. Periphyton accumulation occurs in shallow waters near shore (in the littoral zone).

In nutrient-enriched lakes and reservoirs, primary producers are often found at high levels and can interfere with the uses of the water body. For example, blooms of phytoplankton may occur when certain types of microscopic phytoplankton grow quickly in the water, forming visible patches. Such nuisance phytoplankton blooms are frequently caused by diatoms or cyanobacteria.

In lakes and reservoirs that are warm all year, biomass production is balanced throughout the year. In lakes in temperate environments, however, there is much seasonal variability in primary production and species composition. The amount of primary production is low in winter in temperate water bodies. Small, motile algae are likely to dominate in winter (Wetzel 2001). From spring through fall, blooms of different types of phytoplankton are most likely to occur in lakes and reservoirs in temperate regions. For example, blooms of diatoms are likely to occur in spring and fall when nutrient levels are often high. Dominance by green algae may follow the dominance by diatoms. In summer when nutrients levels are likely to be low (particularly nitrogen), blooms of cyanobacteria are common (Horne and Goldman 1994, Wetzel 2001). Depending on the environmental conditions, much variability in biomass production can be expected from year-to-year.

Although research into lakes and reservoir productivity has focused on phytoplankton productivity, contributions of macrophytes and periphyton can also be important. Most lakes and reservoirs are small so that the ratio of the littoral zone to pelagic zone is large. For these water bodies, macrophytes and periphyton may have a major impact on the lake ecosystem. Horne and Goldman (1994) report that emergent reeds and submerged macrophytes are the dominant primary producers and contribute the most biomass in small lakes. Wetzel (1975, p. 418) states, "In most lakes, the littoral complex of macrophytes and associated microflora is foremost in regulation of rates of eutrophication and in functional impact on the system as a whole."

Cyanobacteria

Species of cyanobacteria, also called blue-green algae, vary widely in growth habits and characteristics. They are the primary nitrogen fixers in most lake and reservoir systems, however, not all cyanobacteria are nitrogen fixers. Cyanobacteria can be expected to have a negative effect on the capabilities of lakes that have aquatic life support, recreation, and water supply designated uses. Cyanobacteria are less suitable as food sources for zooplankton than other phytoplankton species; therefore, blooms of cyanobacteria will have a negative effect on higher trophic levels, including fish. Some cyanobacteria species release toxins to the water column that can be harmful to consumer organisms, including zooplankton and fish. Blooms of some species of cyanobacteria will also cause water clarity to exhibit greater decline than occurs in response to an equivalent biomass of green algae species and thus will have a negative effect on the recreational suitability of water bodies. In reservoirs used as water supplies, blooms of cyanobacteria can result in increased treatment requirements for several reasons. Bloom conditions for species of cyanobacteria have been observed to (1) reduce filter operation efficiency due to the presence of floating mats, (2) increase intensity and frequency of taste and odor episodes due to the secretion of extracellular metabolites (ECM's), and (3) enhance the formation of regulated disinfection by-products from the reaction of chlorine with ECM's (Hyenstrand *et al*. 1998, Dokulil and Teubner 2000).

Several characteristics of cyanobacteria contribute to their capability to dominate under eutrophic conditions (Dokulil and Teubner 2000). Cyanobacteria are known to have lower light intensity requirements than other algal species, which allows them to have a competitive advantage under darkened environments such as those that occur under eutrophic conditions. Non-N-fixing cyanobacteria are believed to have a limited capability to assimilate nitrogen as NO_3^- but are highly competitive for ammonium-N (Blomqvist *et al.* 1994, Hyenstrand *et al*. 1998). This nitrogen-species preference can provide a competitive advantage for non-N-fixing cyanobacteria under eutrophic conditions that accelerate the accumulation of particulate organic nitrogen and consequently leads to oxygen depletion in the subsurface. The resultant anoxic conditions allow conversion of organic nitrogen to NH_4^+ but hinder NH_4^+ conversion to NO_3^- and stimulate denitrification losses of NO_3^- to gaseous forms. Cyanobacteria tend to be excellent competitors for phosphorus at relatively high concentrations characteristic of eutrophic systems but less successful at lower concentrations (Suttle and Harrison 1988). Some species of cyanobacteria are able to regulate their buoyancy, allowing them to move vertically in the water column to take advantage of differential vertical availability of light and nutrients (Klemer and Kanopka 1989). Some of these buoyancy-regulating species also have a capability to assimilate

and store phosphorus internally, allowing them to obtain phosphorus from the sediments and gain a competitive advantage under conditions of phosphorus limitation (Hyenstrand *et al.* 1998).

Numerous factors influence cyanobacterial dominance. Due in part to the variety of species and species properties within the cyanobacteria group, the capability to predict conditions that will cause cyanobacteria blooms is fairly rudimentary. There is no single factor or theory that adequately explains or predicts cyanobacterial dominance (Hyenstrand *et al.* 1998). For example, although cyanobacterial dominance often occurs under eutrophic or hypertrophic conditions, there have been instances where cyanobacterial dominance has occurred under oligotrophic conditions. Working in shallow Danish lakes, Jensen *et al.* (1994) found different groups of cyanobacteria to be dominant under low N:P ratios and high phosphorus conditions.

It has also been observed that inorganic nitrogen speciation can affect algal species dominance. One study of the Occoquan Reservoir in Virginia found that changes in the inorganic nitrogen supply from ammonium to nitrate were accompanied by shifts in algal species dominance away from cyanobacteria and towards green algae and diatoms (T. Grizzard, personal communication). The observed shift was also found (at least anecdotally) to have beneficial impacts on water treatment operations.

In addition to nutrient-related factors, other water body properties can contribute to the growth of cyanobacteria. Because cyanobacteria have a high affinity for carbon as HCO_3^-, conditions of low pH have been demonstrated to increase the potential for cyanobacterial dominance. Elevated water temperatures and high availabilities of trace elements are also favorable conditions for cyanobacterial development. Because cyanobacteria have higher requirements for trace elements than other algal forms, their development is hindered in water bodies with low trace element concentrations. Working with data derived from southeastern lakes and reservoirs (predominantly reservoirs, extending from Mississippi to Maryland), Reckhow (1988) found the probability of cyanobacteria dominance to increase with increasing TP, decreasing TN (and thus, by inference, decreasing TN:TP ratios), and increasing hydraulic residence time. Cyanobacterial dominance also tended to be associated with anoxic conditions in the hypolimnion.

SECTION I-C. PROBLEMS ASSOCIATED WITH EXCESS NUTRIENTS IN LAKES AND RESERVOIRS

Although an excessive supply of nutrients in lakes and reservoirs can lead to eutrophication, the nutrients themselves generally do not interfere with the designated uses. Instead, it is the trophic response to the nutrient enrichment that causes most of the problems. Such responses include heavy growth of phytoplankton and macrophytes and reduced levels of oxygen (particularly in the hypolimnion). Thus most problems caused by excess nutrients are related directly or indirectly to the excessive growth of primary producers (phytoplankton, macrophytes, and periphyton).

The first question for protecting any water body is "What are the uses to be protected?" Water quality managers must consider the intended use of the water (*e.g.*, aquatic life support, recreation, flood control, hydroelectric power generation, drinking water supply, *etc.*). The assignment of uses needs to be clear. Not every lake and/or reservoir will need to meet every

use. For example, many lakes in the nation are not designated for water supply use. Designated uses are often categorized into aesthetic/recreational, aquatic life, and water supply uses. Some ways that lakes and reservoirs can be impaired by nutrients or the trophic response to nutrients are provided. The effects from depletions in dissolved oxygen, fluctuations in pH, impacts of toxins, changes in the aquatic life community, and formations of disinfection byproducts in drinking water are also described.

- Aesthetic and recreational use impairments
  -- Excessive and visible algal growth is unappealing to many swimmers and other lake/reservoir users.
  -- Excessive algal growth causes slippery rocks in the shallow reaches of lakes or reservoirs and can be hazardous for users who walk or play in these regions.
  -- Fishing lures may become tangled in excessive growth of algae and macrophytes.
  -- Boat propellers may get tangled by excessive growth of some types of aquatic vegetation.

- Aquatic life use impairments
  -- Depletion of oxygen concentrations may stress or kill aquatic life.
  -- Fluctuations in pH values may negatively impact aquatic life.
  -- Toxicity may result from high ammonia levels (*e.g.*, > 1 mg/L NH_3-N).
  -- Some algal blooms may release toxic compounds (*e.g.*, cyanotoxins).
  -- A loss of diversity and other changes in the aquatic plant, invertebrate, and fish community structure may result.

- Drinking water and industrial water supply use impairments
  -- Diatoms and filamentous algae can clog water intake screens and filters in water treatment plants.
  -- Decay of algae may lead to taste and odor problems in drinking water.
  -- Hypolimnetic oxygen depletion can lead to a release of iron and manganese in the sediment, causing taste and staining problems in drinking water unless treated.
  -- Water treatment costs may rise for waters drawn from eutrophic sources by requiring more backwashing, treatment, *etc.*
  -- Disinfection byproducts (*e.g.*, trihalomethanes, haloacetic acids), which pose a potential risk to human health, may form during treatment of eutrophic waters to produce drinking water.
  -- Increased risk of bacterial growth in drinking water because of fouling within the distribution system and the increased nutrient content of the water.
  -- Methemoglobinemia (blue-baby syndrome) may affect infants if nitrate levels >10 mg/L in drinking water.

1. Dissolved Oxygen Depletion

Dissolved oxygen (DO) is the soluble form of oxygen found in lakes and reservoirs. Low levels of DO have both direct and indirect effects on the uses of lakes and reservoirs. Excessive growth of primary producers may lead to low DO concentrations, particularly in the hypolimnion. Although primary producers generate oxygen during photosynthesis, they also use oxygen for

respiration, a process that continues even at night when photosynthesis has ceased. Furthermore, as primary producers die, they are decomposed by bacteria that consume oxygen, and large populations of decomposers can consume large amounts of dissolved oxygen.

Because fish and other aquatic organisms obtain oxygen from the water as DO, the amount of DO in the water directly affects aquatic life. Many aquatic insects, fish, and other organisms become stressed and may even die when DO levels drop below a particular threshold level (*e.g.*, below 5 mg/L). For this reason, therefore, states and tribes currently have ambient freshwater DO criteria to protect aquatic life.

In addition to the direct influence that oxygen concentrations can have on aquatic life, low oxygen levels may also have indirect effects on aquatic life as well as on the taste and odor of drinking water. Low DO levels may cause nutrient releases from sediment. For example, when oxygen is present, ferric ions (an insoluble form of iron, Fe^{3+}) and phosphates (PO_4^{3-}) form complexes and sink to the sediment so that the phosphate is unavailable to primary producers. Under low oxygen (anoxic) conditions, however, the iron is transformed to its reduced state (a soluble form of iron, Fe^{2+}), whereby the ferrous ions and phosphates are released to the water. If phosphates enter the productive zone, they could stimulate additional algal growth. As these algae die and subsequently decay, additional oxygen is required, which could potentially lead to more anoxic conditions and additional releases of nutrients from the sediment (Brönmark and Hansson 2005).

In addition to releasing ferrous ions from the sediment, reduction-oxidation reactions also occur under anoxic conditions to reduce particulate manganese oxides (Mn^{4+}) to dissolved manganese (Mn^{2+}). Likewise, under anoxic conditions, sulfate (SO_4^{2-}) in the sediment is converted to hydrogen sulfide (H_2S), which can be toxic to bottom-dwelling organisms. Furthermore, hydrogen sulfide, iron, and manganese are undesirable in drinking water because they are associated with odor, taste, and staining problems. When a lake or reservoir has high levels of these substances and is used for potable water supply, additional treatment is needed for their removal (Cooke and Carlson 1989, Horne and Goldman 1994). The treatment often involves some form of oxidant (*e.g.*, chlorine) that may form harmful disinfection byproducts in the presence of organic matter (see below: Production of Disinfection Byproducts in Drinking Water).

2. pH Fluctuations

The pH of water is a measure of its acid-base condition (range: 0 – 14, with 7 being neutral, less than 7 indicating acidic conditions, and greater than 7 indicating basic conditions). The pH is controlled by the production of hydrogen ions (H^+) and hydroxyl ions (OH^-). Daily fluctuations of water column pH can be caused by excessive primary production.

When photosynthesis is occurring, the water column pH level tends to be more basic. During photosynthesis, carbon dioxide (CO_2) and water are converted by sunlight into oxygen and sugar (glucose, $C_6H_{12}O_6$). During the formation of glucose, hydroxyl ions are produced. These hydroxyl ions raise the water column pH (make it more basic). Furthermore, the removal of

dissolved CO_2 for photosynthesis results in lower levels of carbonic acid (H_2CO_3) in the water column, which causes a shift to a less acidic condition (more basic condition).

More acidic conditions occur at night when photosynthesis ceases but respiration continues. Respiration results in the release of CO_2 into the water and thus increases the production of carbonic acid:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3.$$

Carbonic acid dissociates, producing hydrogen ions that lower the water column pH ($H_2CO_3 \rightleftharpoons HCO_3^- + H^+$).

Extremes in pH are stressful and can even be deadly to aquatic organisms. High pH levels increase the toxicity of some substances, such as ammonia, whereas low pH levels can make heavy metals in the sediment more mobile. Water column pH also affects the availability of phosphorus for algal intake, with phosphorus being unavailable to algae at high and low pH levels. High pH levels can damage fish gills, eyes, and skin. Low pH levels can interfere with fish reproduction. Levels of pH too high (*e.g.*, > 9) or too low (*e.g.*, < 5) can kill aquatic life.

3. Release of Toxins

Some kinds of primary producers release toxins that can kill fish and other organisms. These toxins can taint drinking water supplies and recreational waters. For example, the deaths of livestock have been attributed to drinking water contaminated with toxin-producing cyanobacteria (Bowling and Baker 1996). Humans who drink or swim in water that contains high concentrations of toxins from cyanobacteria may experience gastroenteritis, skin irritation, allergic responses, or liver damage (CDC 2004). To protect human health from toxins produced from harmful algal blooms, the World Health Organization recommends maintaining cyanobacteria levels below certain thresholds (*e.g.*, keeping recreational waters below 20,000 cyanobacterial cells/mL to protect against irritative or allergenic health effects) (Chorus and Bartram 1999).

4. Changes in the Aquatic Life Community

The effect of nutrient enriched waters on the aquatic life in lakes and reservoirs depends on many factors. In some instances, nutrient inputs to lakes and reservoirs can be utilized by the existing aquatic organisms without causing measurable changes in the community structure. In other situations, excessive levels of nutrients can increase the amount of primary production, which then may support a more productive system (one that has a similar taxonomic composition but more individuals). As a third possible response, the taxonomic composition and structure of aquatic communities may also change with the addition of nutrients. Such changes could include the loss of certain species and a shift in the dominance of a particular taxonomic group or groups able to tolerate the new conditions.

5. Production of Disinfection Byproducts in Drinking Water

Most public water supplies in the U.S. are treated with some form of disinfection to protect consumers against bacteria and parasites that may be present in the water. Chlorine, ozone,

chloramines, and chlorine dioxide are commonly used disinfectants. When these disinfectants react with organic matter (*e.g.*, decaying vegetation) found in the water, byproducts form that may be hazardous to human health if consumed over long periods of time. For example, the disinfectant byproducts trihalomethanes (THMs), haloacetic acids (HAAs), and bromate are potentially cancer causing agents. Chlorite, another common byproduct, is known to cause anemia and affect the nervous system of infants and young children. The U.S. EPA has thus set monitoring requirements and maximum contaminant levels (MCLs) for some of the more common byproducts (THMs: MCL = 0.080 mg/L annual average; HAAs: MCL = 0.060 mg/L annual average, bromate: MCL = 0.010 mg/L annual average; and chlorite: MCL = 1.0 mg/L monthly average) (U.S. EPA 2003b).

SECTION II — WHAT WE KNOW

SECTION II-A. DIFFERENCES BETWEEN NATURAL LAKES AND RESERVOIRS

Reservoir Limnology: Ecological Perspectives was written in part to compare and contrast lakes and reservoirs (Thornton *et al.* 1990). Sections of the book are summarized here, and examples from other studies are provided. Although there are many similarities between lakes and reservoirs, this section focuses on the differences. Distinctions between natural lakes and reservoirs and how these distinguishing characteristics could potentially impact nutrient criteria development are explored in general below and in more detail in the following sections.

Physical, chemical, and biological differences in 309 natural lakes and 306 constructed reservoirs were compiled by Cooke and Carlson (1989), citing data from Walker (1981), and are summarized in Table II-1. As may be seen from the table, there are some striking differences, most of which may be related to the "human" purposes that reservoirs are generally constructed to serve. For example, substantial differences in unit surface area loadings of both nitrogen and phosphorus are evident. In fact, reservoirs were found, on average, to exhibit areal phosphorus loading rates over three times greater than those of natural lakes (from Zipper *et al*. 2004).

Table II-1. Comparison of Characteristics (Within Group Means) of Natural Lakes and Reservoirs (Source: Cooke and Carlson.©1989 by AwwaRF and AWWA. Reprinted with permission).

Variable	Natural Lakes (N=309)	Reservoirs (N=306)	Probability Means are Equal
Drainage Area (km^2)	222.0	1358.0	<0.0001
Surface Area (km^2)	5.6	8.6	<0.0001
Maximum Depth (m)	10.7	15.8	<0.0001
Mean Depth (m)	4.5	5.7	<0.0001
Hydraulic Residence Time (yr)	0.74	0.23	<0.0001
Drainage Area(km^2)/Surface Area(km^2)	33.0	156	<0.0001
Transparency (m)	1.4	1.2	<0.0005
Total Phosphorus (mg/L)	0.054	0.053	<0.02
Chlorophyll a (micrograms per liter)	14.0	10.0	<0.0001
P loading (gms P per m^2 per year)	0.87	2.9	<0.0001
N loading (gms N per m^2 per year)	18.0	45.0	<0.0001

Reservoirs are often considered to be hybrids of lakes and rivers (Søballe *et al*. 1992, Kimmel *et al*. 1990, Thornton 1990a). In many ways, reservoirs are intermediate to lake and river systems. For example, reservoirs tend to be intermediate to lakes and rivers in their morphological (shape) and hydrological attributes, the importance of external and internal sources of nutrients, and the

input of organic matter from outside the system (allochthonous) and from within the system (autochthonous) (15 citations in Kimmel *et al*. 1990). Characteristics of individual reservoirs vary extensively; some reservoirs more closely resemble lakes whereas others are more similar to rivers. For example, run-of-the-river reservoirs are usually turbid and have short hydraulic residence times so are more similar to rivers, whereas many tributary-storage reservoirs tend to have characteristics that are more like natural lakes (Kimmel *et al*. 1990, Kennedy 2001).

1. Difference in Nutrient Input, Cycling and Export

Compared to natural lakes, reservoirs tend to be more influenced by nutrients and other substances transported from the surrounding land. Main differences between lakes and reservoirs that impact the input of nutrients include the location within the watershed, comparative size of the catchment area, the shape of the water body, and the quality of inflowing water.

- Within a watershed, natural lakes are generally located near the headwaters whereas reservoirs tend to be located further downstream. Many reservoirs, particularly mainstem-storage reservoirs, are located near the mouth of large basins (Kennedy 2001). The lower position in the watershed for reservoirs means they are fed by larger drainage areas and are fed by higher-order streams compared to lakes (Thornton 1990a, 1990b).
- Reservoirs typically have much larger watersheds than natural lakes of comparable size. In the samples compiled by Cooke and Carlson, the ratio of drainage area:pool area was almost five times larger for constructed impoundments. This trait exposes reservoirs to higher mass fluxes of constituents (including nutrients) carried in tributary streamflows (from Zipper *et al*. 2004).
- Lakes are more circular in shape whereas reservoirs are long, narrow, and dendritic (tree-like). The shape of reservoirs has been shown to increase contact with the terrestrial ecosystem by a factor of 4 to 8 compared to natural lakes (Søballe *et al*. 1992). This difference can be described by the shoreline development ratio, which measures the actual shoreline length to the circumference of a circle that has the same surface area (A perfectly round lake or reservoir would have a shoreline development ratio of 1). Many glacial lakes in the U.S. have shoreline development ratios between 1.5 and 2.5 (Hutchinson 1957 in Søballe *et al*. 1992). In comparison, Søballe *et al*. (1992) found U.S. Army Corps of Engineers reservoirs in the Southeast to have a median shoreline development ratio of 12.
- Wetland areas of natural lakes filter incoming runoff from adjacent land and prevent some nutrients from reaching the lake system. In contrast, many reservoirs lack well-established wetlands because of common fluctuations in water levels and thus have diminished runoff filtering capabilities (Wetzel 1990, Søballe *et al*. 1992). Furthermore, the flow from one or two main tributaries serves as a much more important source of water for reservoirs, and this incoming water often carries large sediment and nutrient loads (Kennedy and Walker 1990, Thornton 1990b, Wetzel 1990).

Nutrient circulation within reservoirs differs from that in lakes primarily because of density flows, advective flow, and a longitudinal (from upstream to downstream) gradient:

- Density flows consist of incoming water of a different density than that in the lake or reservoir. Density flows may enter at the surface, middle, or bottom regions (Ford 1990,

Kennedy and Walker 1990, Søballe *et al*. 1992). When lakes and reservoirs are stratified, incoming nutrients may be isolated to a particular vertical layer. For example, if the incoming water is denser, it will flow to the bottom of the basin where its nutrients will be unavailable to phytoplankton in the epilimnion (Kennedy and Walker 1990). Because reservoirs receive the majority of incoming water from a continuous source of one or two large tributaries, density flows have a much larger impact on reservoirs than on lakes (Ford 1990, Kennedy and Walker 1990).

- Advective flow is the overall movement of water due to currents caused by inflows, outflows, and wind (Ford 1990). This flow is generally minimal in natural lakes but is pronounced in reservoirs. Advective flow contributes to reservoirs having a shorter hydraulic residence time than lakes; short residence times provide less time for phytoplankton to obtain nutrients from the water and to reproduce and grow in population (Søballe and Kimmel 1987).
- In reservoirs, advective flow in conjunction with a deepening basin as the water flows from the river to the dam often causes a continuous longitudinal gradient. This upstream-to-downstream gradient affects the bottom substrate and shape of the reservoir, the velocity of the water, water temperature, sediment and nutrient loads within the reservoir, and the biotic community (6 citations in Søballe *et al*. 1992) (For more information, see Section II-B). In contrast, lakes lack a longitudinal gradient.

The loss of water from natural lakes and reservoirs can differ in a number of ways that impact nutrient levels within the system and in downstream receiving waters. Natural lakes lose water and thus nutrients from surface overflows following snow melts and heavy rains. These events tend to be infrequent. The loss of nutrients from reservoirs, however, is controlled by the operation of the outlet structure. Depending on the dam design, the outlets can discharge water from the top, midsection, and/or bottom of the dam. Reservoirs that release water from the surface act more like natural lakes (Ford 1990). The amount, timing, and frequency of reservoir releases influence the water quality of the reservoir and the export of nutrients. For example, reservoirs used for flood control can have infrequent releases, whereas reservoirs used to generate power may have daily releases (Kennedy 2001). Because of large drawdowns in some reservoirs, wide fluctuations in water levels are possible. As water levels drop during these large drawdowns, the water and nutrients from inlets are forced into the deeper regions and thereby may serve as a source of nutrients for phytoplankton (Ford 1990) or may exit the reservoir and impact the downstream waters. More information on how the structure and operation of dams affects nutrients in reservoirs is provided in Section II-B.

2. Differences in Primary Production Levels

In *Developing Eutrophication Standards for Lakes and Reservoirs*, the North American Lake Management Society (1992) states, "For the purposes of this document, perhaps the most important distinction between rivers, reservoirs, and lakes is that of algal abundance per unit of phosphorus" (p. 9). Canfield and Bachman (1981) examined data from more than 700 natural lakes and reservoirs and compared their nutrient and response parameters. They found that reservoirs usually have substantially lower chlorophyll-*a* levels than natural lakes at the same phosphorus concentrations (Søballe and Kimmel 1987).

Likewise, Cooke and Carlson (1989) reported mean chlorophyll-*a* values of 14.0 µg/L in natural lakes (n = 309) and 10.0 µg/L in reservoirs (n = 306). Based on these overall chlorophyll-*a* values, primary productivity appears to be lower in reservoirs than in natural lakes. Similarly, Søballe and others (1992) found mean and median chlorophyll-*a* values for reservoirs in the southeastern U.S. to be significantly lower than that found in studies of natural lakes by Walker (1981) and Jones and Bachmann (1976). Lower productivity in reservoirs could occur because reservoirs tend to have higher concentrations of suspended solids and shorter hydraulic residence times compared to natural lakes (in Søballe *et al.* 1992: Walker 1984, 1985).

In contrast, based on mean daily productivity (mg C m^{-2} day^{-1}), Kimmel *et al*. (1990) propose that as a group, reservoirs appear more productive than natural lakes. Of 102 natural lakes included in studies by Wetzel (1983) and Brylinsky (1980), the majority were considered oligotrophic, and only 14% of natural lakes were categorized as eutrophic (Table II-2). Of 64 reservoirs, about half were considered mesotrophic and a third were classified as eutrophic (Kimmel *et al*. 1990). Kimmel *et al*. (1990) did not report the levels used to distinguish between eutrophic, mesotrophic, and oligotrophic conditions (ultra-oligotrophic conditions were described as having mean phytoplankton production rates of < 50 mg C m^{-2} day^{-1}).

Table II-2. Percentage of oligotrophic, mesotrophic, and eutrophic states for natural lakes and reservoirs based on mean daily production, as reported in Kimmel *et al*. 1990.

	Natural Lakes (n = 102) Brylinsky 1980, Wetzel 1983	**Reservoirs** (n = 64) Kimmel *et al*. 1990
Oligotrophic	46 %	16 %
Mesotrophic	40 %	52 %
Eutrophic	14 %	33 %

Higher primary productivity in reservoirs compared to natural lakes could occur because of higher annual nutrient loads. These higher nutrient levels in reservoirs may result from the factors listed earlier in this section. Additionally, the geographic distribution of lakes and reservoirs could skew the data. Most reservoirs are located wherever natural lakes are absent, which means in the U.S. reservoirs have a more southern location compared to natural lakes. Thus, reservoirs in the U.S. tend to have warmer waters and longer growing seasons (Thornton 1990a).

The discrepancy between which are more productive natural lakes or reservoirs may result from the variability found among these systems. For example, the data analyzed by Kimmel *et al*. (1990) had productivity rates that ranged from 3 to 5529 mg C m^{-2} day^{-1} for the natural lakes and from 67 to 3975 mg C m^{-2} day^{-1} for the reservoirs. Reservoirs in particular exhibit variable conditions that can influence productivity. For example, in comparing tributary-storage reservoirs and mainstem-storage reservoirs in the Southeast, Søballe *et al*. (1992) found mainstem-storage reservoirs to have higher areal loadings of phosphorus (seven times greater) and nitrogen (six times greater), lower chlorophyll concentrations per unit phosphorus, and lower transparencies per unit of chlorophyll than tributary-storage reservoirs. Thus, making

generalizations is very difficult because individual lakes and reservoirs exist in various geographic locations and have widely differing structural and hydrologic conditions.

3. Differences in Modeling Nutrient-Related Processes

Empirical models, such as nutrient-loading models, identify patterns within data sets. Regression analysis is applied in empirical models whereby the value of a known variable is used to predict the value of an unknown variable. Empirical models should not be used for water bodies that lie outside the range of data used to calibrate the model. Nutrient-loading models were originally designed and calibrated from data collected from natural lakes (*e.g.,* model in Vollenweider 1969), and subsequent models are based on these early models (*e.g.,* Canfield and Bachman 1981). Because of the differences between natural lakes and reservoirs, empirical models developed from natural lakes tend not to work well in reservoirs (in Kimmel *et al.* 1990: Lind 1979, Placke and Poppe 1980, Hannan *et al*. 1981, Higgins *et al*. 1981, Gloss *et al*. 1981, Placke 1983). For example, Smith (1990) concluded that both summer mean algal biomass and the relative biomass of cyanobacteria in four North Carolina reservoirs characterized by high levels of non-algal turbidity were lower than predicted by models developed in natural lakes.

Potential reasons why empirical models developed for use in natural lakes may not work well in reservoirs include the following (Kennedy and Walker 1990, Kimmel *et al*. 1990, Zipper *et al*. 2005):

- Most of the analyses of trophic state (*e.g*., Carlson's TSI) are based on the relationships of phosphorus, chlorophyll-*a*, and water transparency (Secchi disk depth) in northern natural lakes. These relationships are less robust in reservoirs. For example, Reckhow (1988) found a weak relationship between chlorophyll-*a* and phosphorus concentrations ($r^2 = 0.10$) in reservoirs. In contrast, natural lakes tend to have close associations between these two variables ($r^2 \sim 0.70$) (Brown *et al*. 2000). As another example, a study of more than 700 natural lakes and reservoirs from throughout the U.S. indicated that chlorophyll-*a* relationships with TP and Secchi depth were far more variable in reservoirs than in natural lakes (Canfield and Bachman 1981).
- Most models are developed with the assumption that phosphorus is the primary factor limiting algal growth (Kimmel *et al*. 1990). Other nutrients, such as nitrogen (see Section I-B, "Nutrient Limitation"), or other factors may also limit algal production, particularly in reservoirs. For example, light is often the primary factor limiting algal growth in turbid reservoirs (in Kimmel *et al*. 1990: Kimmel and Lind 1972, O'Brien 1975).
- Reservoirs frequently have high levels of suspended sediment that contain phosphorus. Thus, much of the phosphorus in reservoirs exists in the particulate form, and this form is not biologically available for use by primary producers. Thus, although reservoirs may have high loads of phosphorus, the supply may not translate to higher levels of biologically available forms of phosphorus (Canfield and Bachmann 1981).
- Hydrologic differences between lakes and reservoirs would not be accounted for in models developed for natural lakes. Hydraulic residence time, density flows, fluctuations in water levels, and discharges as described earlier differ between natural lakes and reservoirs. These differences affect nutrient availability and primary productivity and therefore potentially affect the ability of models to predict the trophic condition of

reservoirs. For instance, the location of the dam outlet influences temperature characteristics within reservoirs and creates a source of variability that is not present in natural lakes.

- Longitudinal gradients of the factors controlling trophic state exist in reservoirs but are lacking in natural lakes. The location of monitoring points within the reservoir, therefore, could determine the trophic state classification. A single reservoir can grade from eutrophic in its upper reaches to oligotrophic near the dam (Kimmel and Groger 1984, Kimmel *et al.* 1990, Søballe *et al*. 1992). Thus, predictions from spatially averaged conditions may not accurately describe the trophic state of reservoirs (Kennedy and Walker 1990).

SECTION II-B. IMPOUNDMENT ISSUES THAT AFFECT NUTRIENTS

Wetzel (1990, p. 237) writes, "The irregular and extreme variations in physical factors in many reservoirs frustrate our search both for unity and order and for generalized management techniques among these ecosystems." In comparison to natural lakes, nutrient processes in reservoirs are the same, but "…the input variables [for reservoirs] are more complex and dynamic than in many natural lakes" (Wetzel 1990, p.237).

1. Dam Effects

Dams allow water to be stored and retained for subsequent controlled release. Thus, dams serve two main purposes: to store water and raise water levels. Because dams vary tremendously in size (height and width), they also vary greatly in the amount of water storage. For example, a dam on a run-of-the-river reservoir will usually be relatively low and thus consequently, yields a small storage volume and hydraulic head, and a short residence time. In contrast, a tributary-storage dam is typically tall and thus has a large storage volume and hydraulic head, and a long residence time (Søballe *et al*. 1992, U.S. EPA 1993). These differences among reservoirs, which can be attributed to the structure and operation of the dam, affect nutrient processes within reservoirs and in the downstream receiving waters (More information about the impact to downstream waters is in Section II-F.).

Dams often cause a longitudinal gradient from the inflow to the outflow. Based on this gradient, reservoirs can be divided into three zones: riverine, transitional, and lacustrine (Kimmel and Groeger 1984, Kennedy and Walker 1990, Kimmel *et al*. 1990, Søballe *et al*. 1992). The boundaries separating these zones are not distinct and are not fixed (Kennedy and Walker 1990). The zone regions expand and contract in response to watershed runoff events, operation of the dam, and other changes within the reservoir that influence the flow (Kimmel *et al*. 1990).

- The riverine zone is located furthest from the dam and is characterized by having the highest flow velocity and shortest hydraulic residence time. This region tends to receive relatively high levels of nutrients and particulate matter. The turbidity within this zone limits light penetration so primary production can be limited by light in this region.
- The transitional zone is marked by an increase in basin breadth, which allows the water to spread out and thus decrease its velocity. The hydraulic residence time of the transition zone is therefore longer than that in the riverine zone. As the water velocity slows, silt,

clays, and fine particulate organic matter settle out of the water. Light penetration, therefore, increases in this zone. In this region, nutrient recycling begins to become a more important nutrient source than is the input of nutrients from tributaries. It is not uncommon for the transition zone to be the most productive region of the reservoir.

- The lacustrine zone is closest to the dam and most "lake-like" in characteristics. This region of the reservoir has the longest hydraulic residence time, and thus, fine clays and colloidal matter are able to settle out of the water. Most nutrients available for primary production come from within the system. During the growing season, primary production may be limited by nutrients in this zone (Thornton 1990a, Kimmel *et al.* 1990).

Because of the longitudinal gradient, changes in nutrient, sediment, and phytoplankton levels are often apparent from the inflow to outflow reaches of reservoirs (Kennedy and Walker 1990). It should also be noted that other influences may prevent this longitudinal gradient from forming. For example, decreased nutrient input in the upper reaches of Lake Mead due to an upstream reservoir and increased wastewater discharges from Las Vegas to a lower section of the reservoir prevents the formation of the longitudinal pattern typically observed for nutrients (Kimmel *et al*. 1990).

The operation of the reservoir's dam influences the amount of water released, the frequency of the release, and the timing of the release. For example, dams within reservoirs used for flood control are often operated so that water levels are lowered before the predicted flooding season to allow storage of peak flows during heavy precipitation events. These drawdowns decrease downstream high flows, stretch out or increase base flows, and alter the timing of seasonal flows (Petts 1984). Consequently, these changes in flow also change the load of nutrients exiting the reservoirs and thereby affect nutrient concentrations within reservoirs and downstream receiving waters.

As another example, operation of the dam can affect the temperature and material build up of reservoirs. Dams that release water from the top behave more like natural lakes. Discharge from near the surface results in a loss of epilimnion waters (upper layer waters). Since the epilimnion waters are warmer in summer, top releases can cause the reservoir to become cooler during the growing season. In contrast, dams that withdraw water from the bottom, tend to release the cooler, hypolimnion waters plus settling material (including nutrients) (Kennedy 2001). Thus bottom-release dams result in expanding the epilimnion, warming the hypolimnion waters, and weakening the density gradient. Some dams allow releases from different depths so that operators can select from which depth to draw. With this type of dam, the outflow can be limited to a particular layer when the reservoir is stratified (Ford 1990).

2. Sedimentation

Dams have the ability to trap large amounts of sediment. This sediment decreases the storage capacity of reservoirs and thus may impair the function of the reservoir. Reservoirs are often designed to hold an anticipated 100 years worth of sediment. Land use practices that disturb soil can greatly increase the amount of settable material contributed to reservoirs and thus reduce the functional life of the reservoir. For example, sediment yield increased by two orders of

magnitude in regions with extensive road construction (Morris and Fan 1998). Such settlable particles need to be considered when developing nutrient criteria owing to their sorptive relationship with nutrients and their effect on primary production.

The differences in watershed characteristics of lakes and reservoirs, as described in Section II-A, control the quantity of particulate matter delivered to the system. In general, reservoirs have larger catchment areas and greater inflows compared to natural lakes. These factors increase the potential for greater sediment (and nutrient) loads to reservoirs (Thornton 1990b). Because reservoirs are fed primarily by one or two main tributaries, reservoirs are more influenced by precipitation events that carry high but irregular loads of particulate material and nutrients. Furthermore, the high velocity inflows to reservoirs have substantial energy for erosion, and the larger volumes of inflow yield higher sediment-load carrying capacities (Wetzel 1990).

Silt and clay particles have high sorptive capacities, particularly for phosphorus. Therefore, these particles frequently carry high levels of nutrients (in Thornton 1990b: Duffy *et al*. 1978, McCallister and Logan 1978, Schreiber and Rausch 1979, Sharpley and Syers 1979, Sharpley *et al*. 1987). Such nutrient-laden material settles within the reservoir as flow velocities decrease. Sedimentation of entering particulate material is controlled by the settling velocity (rate at which the particle settles, which is influenced by the shape, size, and density of the particle as well as the viscosity and density of the water), settling distance (depth), time available for settling to occur (residence time), and biological processes (*e.g*., intake by feeding zooplankton, resuspension by bottom-feeding organisms) (Jones *et al*. 2004). Thus, physical and biological characteristics control sedimentation.

As described earlier, reservoirs experience longitudinal zones with differing characteristics that influence sedimentation. The riverine zone receives the highest input of particulate matter and is the region where the largest and densest particles settle. Primary production is sometimes limited in this zone because of turbidity (Wetzel 1990). In the transition zone, silts, coarse-to-medium clays, and fine particulate organic matter settle. Although the sorptive capacity of these particles is not as high as that of the fine clays, the loss of nutrients from the water column to the bed occurs with the settling of these particles. Within the lacustrine zone of reservoirs, sedimentation patterns reflect the settling of fine clays and colloidal material (Thornton 1990b).

Turbid waters can limit production by reducing light transmission (Wetzel 1990, Baker 1996). For example, Northcote *et al*. (2005) found phytoplankton biomass to be reduced because of light limitation from turbidity even when the water column contained high phosphate concentrations. Likewise, in an analysis of 64 reservoirs, Kimmel *et al.* (1990) found the most "oligotrophic" reservoir based on phytoplankton productivity estimates (mg C $m^{-2}d^{-1}$) to be limited by light because of turbidity instead of nutrients, as typically indicated by the trophic state classification.

In contrast, nutrient-laden particulate material may contribute to excessive primary production. Because macrophytes obtain most of their nutrients through their roots, sediments with high nutrient concentrations (in regions where macrophytes are able to grow) may contribute to nuisance conditions of these primary producers. Disturbances of the bed by bottom dwelling organisms may cause re-suspension of the sediment and increase the possibility of releasing

nutrients to the water column. Furthermore, under anoxic conditions such as frequently found in the hypolimnion of eutrophic reservoirs, phosphorus may be released from the sediment and possibly made available to primary producers in the water column, thereby stimulating more primary production (Thornton 1990b, Baker 1996).

3. Internal Loading

Whereas external nutrient loading describes the amount of nutrients that enter a lake or reservoir from the drainage area (outside the system), internal loading comes from within the system. Internal loading generally refers to the phosphorus (P) released from anoxic sediment surfaces. Under anoxic conditions, phosphorus may escape from the sediment into the water column and become a nutrient source for algae (Brönmark and Hansson 2005). Internal loading of nutrients is normally low in natural lakes but can be significant in reservoirs (Wetzel 1990).

Even though management practices within the watershed may control the external load of nutrients, internal loading can prevent eutrophic lakes and reservoirs from recovering. Internal loads can be high for decades or centuries (Brönmark and Hansson 2005). In some systems, internal loading represents the main summer phosphorus load. Because it is already within the system, this phosphorus has the potential to greatly impact the water quality and increase primary production.

There are various management practices that can be utilized in the control of internal loading and thus dampen the effects of phosphorus release from sediment. In theory, hypolimnetic aeration or oxygenation should reduce the release of phosphorus from sediments and thereby reduce algal growth. An aeration system that was installed in 1985 in St. Mary Lake, British Columbia was found to maintain DO at 5 mg/L in the hypolimnion and decrease phosphorus concentrations (Nordin *et al.* 1995). Maintenance of oxic conditions in the hypolimnion, however, does not always result in a reduction of productivity and algal growth in lakes. McQueen and Lean (1986) found that hypolimnetic aeration impacted the phosphorus concentrations but did not alter chlorophyll levels. Based on more than 10 years of data on hypolimnetic oxygenation and artificial mixing in two eutrophic lakes, Gächter and Wehrli (1998) found that internal cycling of phosphorus was not affected by increased hypolimnetic DO concentrations. Their research indicated that the sediment-water interface remained anoxic even in the presence of an oxic hypolimnion.

Other methods used in an attempt to fix phosphates within the sediment rely on the additions of substances that promote oxidation-reduction reactions at the sediment surface. Calcium nitrate, $Ca(NO_3)_2$, and a phosphate-binding agent, such as aluminum chloride ($AlCl_3$) or iron chloride ($FeCl_3$), are sometimes added to reservoirs. By using the nitrate as a source of oxygen, the phosphates precipitate as metal complexes and thus become immobilized. Nitrogen gas (N_2) is released as a by-product of the reaction and eventually escapes from the system into the atmosphere (Cooke *et al.* 1993 in Baker 1996; Horne and Goldman 1994; Brönmark and Hansson 2005). Similarly, alum (*e.g.*, aluminum potassium sulfate, $AlK(SO_4)_2 \cdot 12H_2O$) may be added to reduce the internal cycling of phosphorus. The addition of alum should result in the precipitation of phosphates and form a stable floc at the sediment-water interface to prevent internal loading for an extended period of time (Kennedy and Cooke 1982, Cooke *et al.* 1993).

Treatments with alum have been shown to be effective from a few years to over 10 years (Garrison and Knauer 1984 in Baker 1996).

In some reservoirs, dredging may be used to remove nutrient-rich sediment to reduce internal phosphate loading (Peterson 1981 in Baker 1996). Because of the expense involved, dredging is generally limited to small, shallow reservoirs. Care must also be used during dredging to ensure that disturbed substrate is not transported to other areas of the reservoir. For example, when fine silts are dredged, silt screens must be used to prevent suspended silt from being carried along by the water and settling elsewhere. Without changes to the external sources of nutrient loads, dredging results will be temporary because nutrient-enriched sediments begin accumulating immediately.

4. Multipurpose Uses

Reservoirs differ from lakes in that the amount of water they hold is controlled to achieve some beneficial use to society. Whereas reservoirs are generally constructed for a specific purpose, they usually serve several purposes, and these purposes may change with time and often conflict. Common purposes for which reservoirs are constructed include: flood control, water supply, irrigation, navigation, hydroelectric power generation, recreation, wildlife habitat, and water quality maintenance (Martin and McCutcheon 1999) (For more specific examples of uses, see Table II-3).

Table II-3. Examples of designated uses of freshwater reservoirs.

-- Water Contact Recreation	-- Flood Control
-- Noncontact Recreation	-- Commercial and Sport Fishing
-- Agricultural Supply	-- Aquaculture
-- Industrial Process Supply	-- Cold Freshwater Habitat
-- Industrial Service Supply	-- Warm Freshwater Habitat
-- Municipal and Domestic Supply	-- Fish Spawning
-- Hydropower Generation	-- Fish Migration
-- Navigation	-- Rare and Endangered Species
-- Groundwater Recharge	-- Preservation of Biological Habitats
-- Freshwater Replenishment	of Special Significance

Conflicts between the water quality requirements of various uses may be encountered when developing nutrient criteria, particularly for multiple-use impoundments. The Clean Water Act (PL92-500) identifies protection and propagation of fish, shellfish, and wildlife as well as recreation (boating, swimming) as principal designated uses for surface waters. A potential conflict is thus presented between maximizing fisheries productivity (especially for warmwater lakes) and accommodating recreational users. "Pea soup" lakes can be great fish producers but will be shunned by most anglers. Conversely, biologically sterile ("distilled water") conditions may be preferred by some non-anglers. The issue calls for compromise by addressing two questions: 1) "How low must nutrient concentrations be to avoid undesirable plant production?" and 2) "How high must nutrients be to promote good fishing?" (from Zipper *et al*. 2004).

SECTION II-C. ESTIMATING RESIDENCE TIME AND ITS IMPORTANCE IN NUTRIENT CRTIERIA DEVELOPMENT

Water enters lakes and reservoirs from streams and/or rivers, direct precipitation, and subsurface seepage. It exits the system through evaporation, subsurface seepage, and streamflow discharge. The *hydraulic residence time*, sometimes referred to as *hydraulic retention time*, refers to the rate of water movement from inflow to outflow and is measured in units of time (*e.g.*, days, years). Hydraulic residence time (often abbreviated t_w) is calculated by dividing the volume of the lake or reservoir (m^3) by its total annual outflow (m^3/yr). The obtained theoretical hydraulic residence time equals the actual water residence time only if the water moves through the system as a defined water mass (Søballe *et al*. 1992, Baker 1996). In general, water bodies with broad, deep basins (large volumes) tend to have longer hydraulic residence times.

Retention time can refer to the amount of time that nutrient molecules stay within the lake or reservoir. Thus, nutrient retention time may or may not be the same as hydraulic retention time. Sedimentation and nutrient recycling affect the rate of nutrient movement through the system. In winter, nutrient retention time is more likely to be similar to that of hydraulic retention time. In spring, however, nutrients tend to move through the system more slowly because they may be taken up by algae and later released during decomposition (Horne and Goldman 1994).

Hydraulic residence time is related to several important morphological features of lakes and reservoirs and impacts both physical and biological processes within lakes and reservoirs (Søballe *et al*. 1992). For example, hydraulic residence time has the potential to influence the type and rate of biogeochemical cycling, the settlement of particulate matter, and the occurrence of thermal stratification (Morris and Fan 1998, Kalff 2002). Hydraulic residence time thus impacts nutrient availability, turbidity, and mixing (Adams and Hackney 1992). For these reasons, hydraulic residence time has a significant impact on the structure and function of aquatic communities within lakes and reservoirs (Søballe and Kimmel 1987). Hydraulic residence time also influences the movement and transport of nutrients, sediment, and plankton to downstream receiving waters (Morris and Fan 1998, Kalff 2002).

Among lakes and reservoirs, hydraulic residence times vary greatly. In general, natural lakes appear to have longer residence times than do reservoirs. Data from lakes sampled during U.S. EPA's National Eutrophication Survey (summarized by Walker 1981) reveal a median theoretical hydraulic residence time of 270 days. In comparison, data from U.S. Army Corps of Engineers reservoirs in the southeastern U.S. indicate a theoretical residence time of about 80 days (in Søballe *et al*. 1992, based on data reported by Leidy and Jenkins 1977). Reservoirs in particular have a wide range of residence times. For example, Søballe *et al*. (1992) found mean water residence times among southeast reservoirs to range from one day to three years.

In reservoirs, the structure (size) and operation of the dam controls the hydraulic residence time. For example, Kennedy *et al*. (1981) found that the use of floodgates at Lake Red Rock, a reservoir on the Des Moines River, cut in half the theoretical residence time (in Kennedy and Walker 1990). Consequently, hydraulic residence time determines whether reservoirs are more lake-like or river-like. Reservoirs with short residence times (< 30 – 40 days) (common for run-of-the-river reservoirs) tend to be river-like in their ecological structure and function, whereas

reservoirs with long residence times (> 100 days), typical of tributary-storage reservoirs, are often similar to natural lakes. Reservoirs that have water residence times within these two ranges (about 30 to 100 days) are more variable in their responses, sometimes acting like river systems and other times responding more like lake systems (Søballe *et al.* 1992).

Long hydraulic residence times, in combination with other favorable conditions, allow populations of primary producers to grow and become established within the system. Thus, long hydraulic residence times are associated with higher algal abundances. Based on the results from a study of predominantly glacial lakes, Schindler (1978, p. 484) states: "Two variables, phosphorus input and water renewal time [a transform of residence time that reflects the time required to replace the entire volume of a lake or reservoir]… appear to serve equally well for interpreting production results and are the key to managing a wide variety of aquatic productivity problems."

Numerous studies have shown a strong relationship between hydraulic residence time and primary production (*e.g*., Dickman 1969, Søballe and Kimmel 1987, Ryding and Rast 1989, Maceina *et al*. 1996). In a study of Alabama reservoirs, Maceina *et al*. (1996) found hydraulic residence time, mean depth, and TP to be significant determinants of chlorophyll-*a* concentrations. Likewise, Søballe and Kimmel (1987) found a relationship between hydraulic residence time, TP, and algal cell counts. Algal abundance per unit phosphorus increased from rivers to impoundments to natural lakes, which also reflected a parallel increase in hydraulic residence time. Furthermore, when rivers, impoundments, and natural lakes had similar hydraulic residence times, their algal abundance per unit phosphorus did not differ significantly (Søballe and Kimmel 1987).

Because hydraulic residence time affects the population growth of primary producers, lakes and reservoirs can be classified by hydraulic residence time as a part of nutrient criteria development. For example, in *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs*, U.S. EPA defines lakes as "natural and artificial impoundments with a surface area greater than 10 acres and a mean water residence time of 14 or more days" (U.S. EPA 2000a, p. 3-1). U.S. EPA further advises that states that have not defined lakes should do so, stating, "The goal of such an exercise is to eliminate small water bodies that, because of their size (and resulting hydrology) or uses (*e.g*., small agricultural impoundments), do not accurately represent typical lake conditions or do not exhibit expected responses to stressors" (U.S. EPA 2000a, p. 3-1).

SECTION II-D. RELATIONSHIP BETWEEN FISHERIES AND NATURAL COMMUNITY[1]

Community energetics dictate that the biomass of fish at or near the top of the trophic pyramid should be highly dependent on the amount of primary production at the base (Lindemann 1942). Primary production in lakes is limited by nutrients, principally phosphorus. U.S. EPA (2000a) notes that nitrogen limitation is largely confined to subtropical and high altitude/latitude lakes. Nitrogen limited waters have TN:TP < 30 (Alam and Glecker 1994).

[1] This section was written by J.J. Ney. Modifications have been made from the original source, Zipper *et al*. 2005.

However, the productivity of a fishery can be limited not only by insufficient energy (food) but also by inadequate habitat. High levels of algal production can cause hypolimnetic oxygen deficits to the detriment of coldwater and coolwater fishes. In shallow lakes, nutrients can stimulate excessive macrophyte growth, reducing habitat for warmwater sportfish species (Wiley *et al*. 1984). The influence of nutrients and resulting primary production on fisheries productivity in lakes and reservoirs should thus be parabolic, with low concentrations of nutrients constraining food supply and high concentrations of nutrients limiting suitable habitat. The nutrient (phosphorus) or response (chlorophyll-*a*, Secchi disk water transparency) parameters that promote healthy fisheries will vary by water-body type and the species-specific requirements of the desired fishes.

This section proceeds from a general overview of the fisheries-water quality relationship to a consideration of the particular nature of that relationship in reservoirs (vs. natural lakes). It concludes with an analysis of water quality requirements for Virginia's three categories of reservoir fisheries: coldwater (trout), coolwater, and warmwater.

1. Overview

Empiric relationships between productivity of fisheries (as measured by fish harvest, production, or biomass) and both primary production and phosphorus concentration have been developed and published for regional and cosmopolitan sets of lakes. Correlations between primary production and fisheries productivity are highly positive, the former explaining (r^2) 67 – 84% of the latter (Table II-4). Correlations between total phosphorus (TP) concentration and fisheries productivity are equally strong (51 – 84%, Table II-5).

2. Water Quality in Reservoirs

Some of the above data sets were limited to natural lakes. Indeed, most of the analyses of trophic state (*e.g.,* Carlson's TSI) are based on the relationships of phosphorus, chlorophyll-*a*, and water transparency (Secchi disk depth) in northern natural lakes (U.S. EPA 2000a). These relationships are less robust in reservoirs. Chlorophyll-*a* concentrations tend to be lower in reservoirs than in natural lakes (Søballe *et al*. 1992) because higher inorganic turbidity and flushing rates in reservoirs may limit the ability of phosphorus to stimulate phytoplankton production. In a regression analysis of about 80 southeastern U.S. reservoirs (from U.S. EPA's National Eutrophication Survey), Reckhow (1988) reported a fairly strong correlation between transparency and phosphorus ($r^2 = 0.50$), a weak relationship between chlorophyll-*a* and phosphorus ($r^2 = 0.10$), and virtually no correlation between chlorophyll-*a* and transparency ($r^2 < 0.01$). In these impoundments, inorganic turbidity largely determined water transparency, and although the suspended sediment contained phosphorus, most of the phosphorus was not biologically available. In contrast, the r^2 for phosphorus concentration vs. chlorophyll-*a* level has been widely reported as ~0.70 (Brown *et al*. 2000) for sets of natural lakes. Canfield and Bachman (1981) examined the National Eutrophic Survey (NES) data set and compared nutrient and response parameters between natural lakes and reservoirs. They also found that reservoirs usually have substantially lower chlorophyll-*a* levels than natural lakes at the same phosphorus concentrations. Interpretation of their scatter diagram indicates that to produce 10.0 mg/m^3 of chlorophyll-*a* (indicative of marginally eutrophic conditions) in the average natural lake would

Table II-4. Predictive relationships between measures of plant and fish productivity in lakes and reservoirs, as determined from single-variable regression models.

Independent Variable	Dependent Variable	Data Set (n)	% of Variation Explained (r^2)	Source
Gross photosynthesis	Total fish yield	Indian lakes (15)	82	Melack (1976)
Phytoplankton standing stock	Total fish yield	Natural lakes, northern hemisphere (19)	84	Oglesby (1977)
Gross photosynthesis	Total fish yield	Chinese lakes and ponds (18)	76	Liang *et al*. (1981)
Chlorophyll-*a*	Sport fish yield	Midwestern U.S. lakes and reservoirs (25)	83	Jones and Hoyer (1982)
Primary production	Total fish production	Cosmopolitan lakes (19)	67	Downing *et al*. (1990)

Table II-5. Relationship between total phosphorus concentration (μg/L) as the independent variable and various measures of fish production in lakes and reservoirs.

Dependent Variable	Data Set (n)	% of Variation Explained (r^2)	Source
Total fish yield	North American lakes (21)	84	Hanson and Leggett (1982)
Sport fish yield	Midwestern U.S. lakes and reservoirs (21)	52	Jones and Hoyer (1982)
Total standing stock	Southern Appalachian reservoirs (21)	84	Ney *et al*. (1990)
Piscivore standing stock	Southern Appalachian reservoirs (11)	51	Ney *et al*. (1990)
Total fish production	Cosmopolitan lakes (14)	67	Downing *et al.* (1990)

require 30 µg/L total phosphorus, whereas the average reservoir would require 40 µg/L total phosphorus.

High flushing rates (low hydraulic residence times) in reservoirs also limit development of phytoplankton biomass. In fact, the *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (U.S. EPA 2000a) recommends that lakes and reservoirs with hydraulic residence times < 14 days be exempted from nutrient regulation because algal biomass buildup is minimal.

Chlorophyll-*a* concentrations have long been recognized as the single best metric for assessing nutrient-induced water quality of lakes because it most directly measures the parameter that affects aesthetic value and recreational use (Carlson 1977, Heiskary and Walker 1988, Bachman *et al.* 1996). Chlorophyll-*a* concentrations would appear to be the parameter of choice as a criterion for nutrient standards for reservoirs because water transparency is affected by inorganic turbidity and phosphorus concentration is irrelevant in impoundments with a low hydraulic residence time.

Reservoirs differ from natural lakes in that they characteristically exhibit a trophic gradient (Søballe *et al*. 1992). As dammed rivers, reservoirs lose nutrients through settling in a downstream direction. Thus a single reservoir may grade from eutrophic in its upper reaches to oligotrophic near the dam. Such systems can support good fisheries for a combination of warmwater, coolwater, and even coldwater fishes.

3. Reservoir Fisheries and Water Quality

Because inorganic turbidity and flushing can limit nutrient impacts on reservoir productivity, it might be expected that the empiric relationship between phosphorus concentration and fisheries would be relatively weak. This does not appear to be the case in large reservoirs of the southeastern United States. Ney *et al*. (1990) examined the relationship between fish standing stock and a variety of potential predictors in a set of 21 southeastern, Appalachian-region, multi-purpose reservoirs for which fishery and water chemistry information was available for the same time frame (within 2 years). These reservoirs varied greatly in surface area (1,700 – 132,000 ha), hydraulic residence time (4 – 438 d), and total fish standing stock (77 – 2,321 kg/ha). Total phosphorus was easily the best predictor of fish standing stock ($r^2 = 0.84$), followed by Secchi disk depth (negative slope, $r^2 = 0.42$) and chlorophyll-*a* ($r^2 = 0.31$). Fish standing stock increased linearly over the range of total phosphorus (8 – 81 µg/L) on a log-log scale, suggesting that maximum fish biomass would occur at higher phosphorus concentrations (Ney 1996). Fish production will ultimately be limited by habitat loss, resulting in a parabolic relationship with nutrient concentrations (Figure II-1).

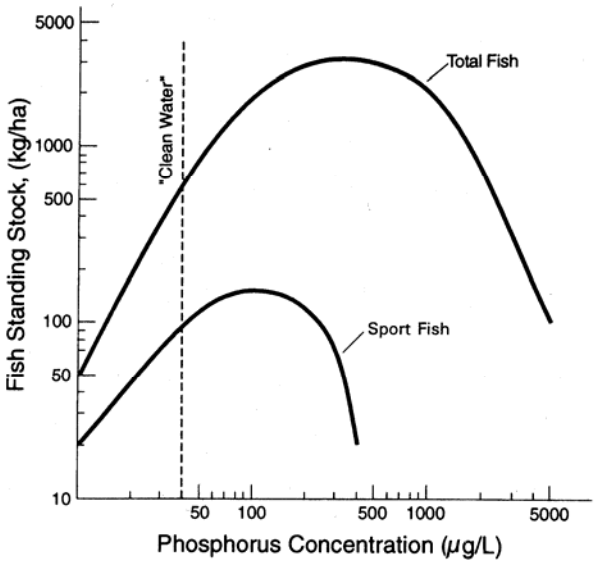

Figure II-1. Generalized relation of total fish and sport fish standing stock with total phosphorous concentration in temperate latitude reservoirs. Standing stock values are representative of southeastern U.S. reservoirs to 100 μg/L total phosphorus (TP), whereas standing stocks at higher phosphorus concentrations are hypothetical. The vertical line labeled as "clean water" represents a TP concentration associated with water clarity that could be considered as minimally acceptable for contact recreational use and is an approximate value. The "clean water" representation is conceptual and is not reproduced here for the purpose of suggesting a specific TP criterion value (Source: Ney. Copyright 1996 by the American Fisheries Society. Reprinted with permission.).

Total fish standing stock or total fish production may not be indicative of sportfishing potential of reservoirs because sport and food fishes usually account for less than half the total. For the southern Appalachian reservoir data set, Yurk and Ney (1989) found that piscivore (largely game fish) standing stock increased linearly over the range of total phosphorus concentrations from 8 to 81 μg/L ($r^2 = 0.51$). Jones and Hoyer (1982) reported that annual sportfish (synonym here for "gamefish") harvest increases linearly with total phosphorus concentrations over the range 15 – 90 μg/L in 25 midwestern U.S. lakes ($r^2 = 0.52$) and with chlorophyll-*a* concentrations between 4 – 67 μg/L ($r^2 = 0.83$). In a study of 21 northern temperate natural lakes, Hanson and Leggett (1982) found that long-term sport and commercial annual harvests increased with total phosphorus concentration up to 500 μg/L ($r^2 = 0.84$).

In contrast to previous studies (Yurk and Ney 1989, Ney 1996), the plots of fishery status vs. water column TP and Chl-a generated by the Virginia Academic Advisory Committee for the Virginia Department of Environmental Quality (VDEQ), did not yield well-defined relationships. Prior studies included only large impoundments (> 1,700 acres), whereas relatively small lakes were heavily represented in the VDEQ database. Thus, this difference in reservoir size is believed to cause the different results. Lakes and reservoirs vary in nutrient response capability due to physical features. Generally, fish populations in small lakes and reservoirs are more subject to influence by non-nutrient factors than fish populations in large lakes and reservoirs.

Non-nutrient factors capable of influencing fish populations include inorganic turbidity (suspended sediments), physical features, and structural elements.

4. Fisheries in Reservoirs in Virginia

The fisheries of Virginia's public reservoirs include coldwater, coolwater, and warmwater fisheries. Coldwater fisheries are managed for trout, and coolwater fisheries are managed for striped bass and walleye. Warmwater fisheries are managed for sunfish, largemouth bass, and catfish. The Virginia Department of Game and Inland Fisheries (VDGIF) manages numerous small reservoirs for sportfishing.

Within the overall sportfish complex, it has long been recognized that individual species respond differently to particular levels of lake fertility. U.S. EPA's *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (U.S. EPA 2000a) cites the work of Oglesby *et al*. (1987) to predict that as phosphorus in natural lakes increases, fisheries will shift from coldwater (TP < 24 µg/L) to coolwater (TP = 24 – 48 µg/L) to warmwater (TP = 48 – 193 µg/L). Total fisheries yield (harvest) should progressively rise over this range of phosphorus concentration. However, these projections were based on rather limited data that has been supplemented by later studies and did not apply specifically to many of the sportfish species of Virginia's reservoirs.

The following was used by the Academic Advisory Committee to the VDEQ to recommend possible nutrient-related criteria for reservoirs in Virginia.

a. Coldwater Fisheries

Trout fisheries in Virginia's lakes are maintained by frequent stockings from hatcheries, either on a put-and-take (adults) or put-grow-take basis (fingerlings). Rainbow, brown, and brook trout are stocked alone or in combination. Because stocked put-and-take trout fisheries are seasonal and not habitat limited, this analysis focuses on conditions necessary for trout to grow and survive over one or more years to reach harvestable size. Essentially, this requires an oxygenated hypolimnion during thermal stratification. The relevant water quality literature is sparse. In Minnesota, natural populations of lake trout (*Salvelinus namayacush)* achieve peak abundance at TP = 6 µg/L and chlorophyll-*a* = 1 µg/L (Schupp and Wilson 1993). However, the lake trout requires the lowest temperatures of any salmonid and does not live in Virginia. In another study, a fertilization experiment in a small mountain lake in British Columbia increased rainbow trout growth and interannual survival when raising TP levels from 4 to 9 µg/L and chlorophyll-*a* concentrations from 1 to 6 µg/L (Johnston *et al*. 1999). Similarly, brown trout abundance in Lake Windemere, U.K. more than doubled when TP was reduced from 30 to 11 µg/L and chlorophyll-*a* levels declined from 30 to 14 µg/L (Elliott *et al*. 1996).

b. Coolwater Fisheries

Virginia's coolwater sportfish species are striped bass, hybrid striped bass (white bass x striped bass), and walleye. The smallmouth bass is sometimes considered a coolwater species, but it has virtually identical temperature tolerances to its congener largemouth bass, a warmwater fish considered below (Brown 1974). All three coolwater species are maintained by the stocking of hatchery-reared fingerlings on a put-grow-take basis in Virginia; the single exception is the striped bass population of Kerr Reservoir, which is self-sustaining.

Walleye, striped bass, and hybrid striped bass prefer water temperatures in the range of 19 – 28^{o}C (Coutant 1985, Hokanson 1990, Kilpatrick 2003). By late summer in Virginia reservoirs, this habitat is usually limited to the metalimnion/hypolimnion down-lake region near the dam (Ney 1988, Kilpatrick 2003). However, all three species can tolerate water temperatures of > 28^{o}C for extended periods without observed mortality, although growth will likely be impaired (Brown 1974, Wrenn and Forsythe 1979, Kilpatrick 2003).

The influence of water quality on walleye abundance has been examined for Minnesota lakes and Lake Erie, which supports the most productive walleye fishery in the world. In Minnesota, walleye abundance peaks under mesotrophic conditions: TP concentrations of 15 – 25 µg/L and chlorophyll-*a* levels of 7 – 10 µg/L (Schupp and Wilson 1993). Lake Erie's walleye populations are thriving at chlorophyll-*a* concentrations of 5 – 15 µg/L; it is actually projected to increase if phosphorus loading is doubled (Anderson *et al.* 2001). Walleye do well in lakes that experience occasional hypolimnetic anoxia but poorly in lakes with Secchi disk transparency > 4 meters (Schupp and Wilson 1993).

Striped bass also fare poorly under oligotrophic conditions. When Lake Mead, Nevada, became oligotrophic (TP = 10 µg/L), striped bass became stunted and emaciated (Axler *et al*. 1987). Smith Mountain Lake, a reservoir formed by the Blackwater and Roanoke rivers, is Virginia's premier inland striped bass fishery and has a classic trophic gradient. The lower segment of Smith Mountain Lake has an oxygenated hypolimnion year-round, providing a summer thermal refuge for striped bass. However, striped bass congregate further upstream in summer where prey fish are more abundant (Ney 1988), suggesting that food is more important than ideal habitat.

In Virginia's large reservoirs, coolwater fishes appear to be more food limited than habitat limited. Virginia's coolwater sportfishes are fast-growing piscivores dependent on a large supply of forage fishes (*e.g*., gizzard shad, threadfin shad). These planktivores are most abundant in fertile systems (Bremigan and Stein 2001, Maceina 2001).

c. Warmwater Fisheries

Principal warmwater sportfishes are primarily of the sunfish family (Centrarchidae) as well as catfishes. Catfishes have higher temperature and lower dissolved oxygen (DO) tolerances than centrarchids and thus are not considered further in this review. Virginia's centrarchids include sunfishes (bluegill, redear, redbreast, and pumpkinseed), black and white crappie, smallmouth bass, as well as the most-sought freshwater sportfish species, largemouth bass. Centrarchids are littoral and epilimnetic fishes that do not require an oxygenated hypolimnion as summer habitat. Nutrient-induced habitat limitations occur only in shallow lakes that become choked with aquatic macrophytes. In such systems, both largemouth bass and sunfish become stunted (Bennett 1962). Virginia has few macrophyte-dominated reservoirs. Where they exist, poor watershed practices (erosion) or invasive exotics (*e.g*., *Hydrilla)* are usually responsible.

For the most part, centarchid populations are food-limited rather than habitat-limited. Higher levels of nutrients translate to more centrarchid biomass. In fact, centrarchid lakes devoted primarily to fishing are often fertilized at least annually. Auburn University, which pioneered

research on centrarchid management, recommends fertilization to achieve chlorophyll-*a* concentrations of 40 – 60 µg/L (Maceina 2001). The Virginia Department of Game and Inland Fisheries frequently fertilizes its small fishing lakes to produce robust centrarchid populations for anglers. In these small (< 200 acres) lakes, chlorophyll-*a* concentrations in the 40 – 60 µg/L range commonly result.

Obviously, larger reservoirs are not subject to direct fertilization because they must accommodate aesthetic and water-contact recreation and (sometimes) coolwater fisheries. However, across reservoirs of all sizes, the pattern of "higher fertility = better centrarchid fishing" holds. In Minnesota, Schupp and Wilson (1993) reported that black crappie fisheries peak at TP concentrations ~60 µg/L and chlorophyll-*a* levels ~20 µg/L; white crappie do best under hypereutrophic conditions (TP ~100 µg/L; chlorophyll-*a* ~60 µg/L).

In a study of 30 large Alabama reservoirs, Maceina *et al*. (1996) found that growth of crappie and largemouth bass increased with increasing chlorophyll-*a* levels up to ~20 µg/L. In fact, the potential for an angler to catch a trophy largemouth bass (> 5 lbs.) was about 3 times greater in eutrophic than mesotrophic lakes. Bachmann *et al*. (1996) confirmed a similar pattern for natural Florida lakes (n = 360): trophy largemouth bass were more abundant in highly eutrophic lakes (chlorophyll-*a* > 40 µg/L), as were populations of redear sunfish and black crappie.

SECTION II-E. RECREATIONAL USER PERCEPTIONS OF LAKE/RESERVOIR WATER QUALITY[2]

The objective of this effort was to evaluate the existing evidence regarding the relationship between observable differences in water conditions (water clarity and/or algal populations) and recreational uses (primarily recreational contact uses such as swimming and aesthetics).

Two general types of studies relevant to the above objective were reviewed. The first type of study examines the user perceptions of the suitability of a water body for recreational contact use (Heiskary and Walker 1988, Smeltzer and Heiskary 1990, Smith *et al*. 1991, Smith and Davis-Colley 1992, Smith *et al*. 1995, and Hoyer *et al*. 2004). These studies typically administer simple survey instruments to solicit respondents' subjective evaluation of the water for either recreational use (swimming/boating) or aesthetic enjoyment. Respondents typically are asked to rank on a five-point scale the suitability of a water body for recreational contact. Survey administrators also frequently ask respondents to provide their subjective evaluation of the physical condition of the water (clear, clean, *etc*.). Statistical correlations are then estimated between respondent rankings and the water quality conditions existing at the place and time the survey was conducted. Water conditions were typically measured as Secchi depth and/or chlorophyll-*a* (Chl-*a*) concentrations.

Much of this literature, however, is not based on representative samples of recreational water users. Rather, members of volunteer monitoring associations or members of state agency staff are asked to respond to most user-perception surveys (Heiskary and Walker 1988, Smeltzer and

[2] This section was written by K. Stephenson. Modifications have been made from the original source, Zipper *et al*. 2005.

Heiskary 1990, Smith and Davis-Colley 1992, Hoyer *et al*. 2004). Thus, the results of these studies do not reflect representative cross-sections of recreational users or the intensity of recreational use across different sites. One study, however, found a close correspondence in the perceptions of recreational suitability between field water quality agency staff and recreational users (Smith *et al*. 1995).

The second type of study examines a landowner's willingness to pay for water quality improvements. These studies, called hedonic price analyses, examined whether statistical relationships exist between observed differences in the prices paid for lake-front property and water quality (Michael *et al*. 1996, 2000; Poor *et al*. 2001; Gibbs *et al*. 2002; Krysel *et al*. 2003). Hedonic price studies attempt to statistically isolate the influence of water clarity on property prices from all other factors that might influence property prices. If two lake-front properties have different levels of water quality but are similar in other dimensions (types of structures on the property, location amenities, *etc*.), then any observed difference in property prices is interpreted as people's willingness to pay for water quality improvements. Water clarity (Secchi depth) is the typical measure of water quality in hedonic price studies since landowner purchasing decisions seemed to primarily be influenced by the visual appearance of the water (Brashares 1985). In these studies, water clarity is often estimated by Secchi depth. Hedonic price studies cannot discern the landowner's interest or use of the water body (swimming, boating, aesthetics, fishing, *etc*.).

It should be noted that most of the studies that investigate the relationship between recreational user perceptions/preferences and water clarity have been conducted in regions with relatively clear lakes. The studies reviewed, with one exception, have been conducted in Minnesota, New Hampshire, Vermont, Maine, Michigan, and New Zealand. The majority of lakes included in these studies are typically oligotrophic or mesotrophic. Secchi depth measurements reported in these studies typically average 3 to 6 meters. Only one study was found that was conducted in the southeastern United States (Florida), and it was dominated by eutrophic lakes (Hoyer *et al*. 2004).

1. General Findings

All studies found that people's perceptions of the desirability of a lake/reservoir for contact recreational uses and aesthetics vary directly with measures of water clarity. User-perception studies found that the desirability/suitability for recreational contact use increases as water clarity increases and Chl-*a* levels decrease. Many studies found that respondents distinguish suitable and unsuitable waters for swimming at Secchi depths ranging between 0.6 meters and 3 meters (Heiskary and Walker 1988, Smeltzer and Heiskary 1990, Smith *et al*. 1991, Smith and Davies-Colley 1992, Smith *et al*. 1995, Hoyer *et al*. 2004). In their Florida study, Hoyer *et al*. (2004) report mean Secchi depth of 2 meters and 1.6 meters for waters where respondents rank water "excellent for swimming" to "slightly impaired" respectively. Heiskary and Walker (1988) conclude that perceptions of recreational use and Chl-*a* levels in Minnesota vary. In their study, respondents generally found waters unsuitable for recreational use when Chl-a levels exceed 40 ppb, but Chl-*a* levels between 15-60 ppb were generally rated as only "slightly impaired" for swimming and aesthetics. Hoyer *et al*. (2004) report that Florida respondents generally rate the

suitability of waters for swimming at mean Chl-*a* levels of less than 15 µg/L. See Table II-6 for a summary.

Hedonic price studies generally find statistically significant and positive relationships between Secchi depth and land prices. Landowners in Maine and Minnesota for example are generally willing to pay 0 to 10% more for water-front property for a one-meter increase in water clarity (Michael *et al*. 1996, Krysel *et al*. 2003).

The limited evidence contained in the studies described here, however, also suggests that perceptions of suitability of water for recreational contact use exhibit considerable variation across regions and people. In the Smeltzer and Heiskary (1990) study, which includes lakes ranging from oligotrophic (northern Minnesota and Vermont) to eutrophic (southern Minnesota), considerable regional variation exists in the respondents' recreational suitability rankings. For example respondents in northern Minnesota and Vermont rank water "excellent for swimming" at Secchi depths ranging from 3 to 5+ meters, whereas the mean response from southern Minnesota respondents range from 0.9 to 2+ meters for excellent swimming. Hoyer *et al.* (2004, p. 247) tentatively conclude that similar patterns exist in Florida, stating "lake users located in areas dominated by eutrophic lakes are more likely to tolerate green water and consider it good water quality."[3] Thus, the literature seems to support the general conclusion that what is considered good water quality is what people are "used to" seeing.

Other findings also confirm that good water quality for recreational uses is relative — water quality perceptions are dependent on users' experiences. Respondents' physical descriptions of water vary across regions. Residents in Vermont called lakes "crystal clear" with Secchi readings of 7 meters, whereas residents in southern Minnesota rated waters as "crystal clear" with Secchi readings of 1.9 meters (Smeltzer and Heiskary 1990). Further, at least one study suggests that users' perception of water quality may be more sensitive to the *change* in water quality levels than to absolute levels (like Secchi depth) (Michael *et al*. 2000).

Most studies also find considerable variation between individual respondents' assessments of the desirability of a lake for recreational contact. For example, Hoyer *et al*. (2004) found that waters ranging from 0.4 to 4.3 meters were ranked by Florida-survey respondents as "excellent for swimming" (mean = 2.0 meters). In the same study, Chl-*a* levels ranging from 1 to 114 µg/L were reported as having "excellent" waters for swimming (mean 11 µg/L). For waters rated as excellent for swimming, Chl-*a* levels falling within the 25th and 75th quartiles were between 2.5 to 10.5 µg/L. The 25th and 75th quartiles for waters ranked as providing substantially diminished swimming opportunities (ranked as a "4") ranged from 2.5 µg/L to 11 µg/L. Thus considerable overlap exists in Chl-*a* readings for waters judged to be excellent and those found to be unsuitable for swimming (Hoyer *et al.* 2004). No similar statistics were reported for Secchi depth. It is unclear whether these large variations are due to differences in individual perceptions of water quality suitability or due to the possibility that the water quality measures (Chl-*a* and Secchi depth) may not adequately reflect the characteristics of a water body that are important to users in determining water quality.

[3] Hoyer *et al*. (2004) also note that water clarity in Florida is particularly important for some recreational contact users due to the presence of alligators in that state.

Table II-6. Summary of Selected Water Clarity Perception Studies.

Study	Location	Surveyed Group	Respondent Ranking	Secchi Depth (meters)	Chl-*a* Level (µg/L)
Hoyer *et al*. 2004	FL	Citizen lake monitors	Excellent for swimming (rank=1,2)	2 to 2.3 (mean) 0.4 – 4.3 (min/max±)	7 to 12 (mean) 2.5 – 10.5 (range+)
			Slightly impaired for swimming (rank=3)	1.6 (mean) 0.4 – 4.3 (min/max±)	14 (mean) 5 – 11 (range+)
			Undesirable (rank=4,5)	0.8 to 1.7 (mean) 0.2 – 5.5 (min/max±)	5 to 80 (mean) 2.5 – 110 (range+)
Smeltzer & Heiskary 1990	Northern MN, VT	Citizen lake monitors	Excellent for swimming (rank=1,2)	3 to 6 (mean)	
			Slightly impaired for swimming (rank=3)	2 to 4 (mean) 1.5 – 4.5 (range+)	
			Undesirable (rank=4,5)	1 to 1.7 (mean)	
Smeltzer & Heiskary 1990	Central, Southern MN		Excellent for swimming (rank=1,2)	0.9 to 2.75 (mean)	
			Slightly impaired for swimming (rank=3)	0.6 to 1.25 (mean) 0.5 – 1.75 (range+)	
			Undesirable (rank=4,5)	0.4 to 0.6 (mean)	
Heiskary & Walker 1988	MN	Agency staff	Excellent for swimming (rank=1,2)	2.5 to 5 (mean) 1.5 – 5 (range+)	5 to 10 ppb (mean) 2 – 17 ppb (range+)
			Slightly impaired for swimming (rank=3)	1 (mean) 0.5 – 1.3 (range+)	45 (mean) 15 – 60 ppb (range+)
			Undesirable (rank=4,5)	0.7 (mean) 0.5 – 1 (range+)	55 ppb (mean) 40 – 75 ppb (range+)
Smith *et al*. 1995	New Zealand	Rec. users	Just suitable or better ranking for swimming	≥ 1.5 (80% users) ≥ 2.75 (90% users)	
Smith *et a*l. 1992	New Zealand	Agency staff	Marginally suitable bathing	1.375 (mean)	
			Suitable for bathing	2.0 (mean)	

± Minimum and maximum values reported for a given respondent water quality ranking

+ Values fall within the 25th and 75th quartiles of all observations

Regional differences in a willingness to pay for water clarity also provide evidence of significant differences in water clarity preferences across users and regions. Hedonic price studies frequently report substantial differences in willingness to pay for one meter improvement in water clarity between lakes within a specific region, indicating that some lake landowners are more sensitive to changes in water clarity readings than their counterparts at other local lakes. In one Maine survey, only a little more than half of all owners of lake-front property stated that water quality entered into their decision of how much to pay for property (Michael *et al*. 2000). Significant differences in the willingness to pay for improvements in water clarity were also found between regions with lakes reporting similar levels of water clarity (Gibbs *et al*. 2002).

Another common conclusion reached in the literature is that the relationship between water clarity and willingness to pay/recreational perceptions is nonlinear (Smith *et al*. 1995, Michael *et al*. 1996, Smith and Perrone 1996, Gibbs *et al*. 2002). Smith *et al.* (1995) found that perceptions of the desirability of a water body in New Zealand suitable for swimming changes significantly between Secchi depths of 0.9 and 1.5 meters. Depths below 0.9 meters were generally judged to be unsuitable for swimming whereas waters above 1.5 meters were generally found to be suitable. Fixed incremental improvements in water clarity above 2 meters did not generate large changes in the users' suitability rankings (Smith *et al*. 1995). Most hedonic price studies also model a property owner's perception to water clarity levels as a nonlinear relationship (Michael *et al*. 1996, Poor *et al.* 2001, Gibbs *et al*. 2002, Krysel *et al*. 2003).

Neither type of study (user surveys or hedonic studies) examines user preferences for recreational uses in a multiuse setting. User-perception surveys do not solicit suitability ratings for other recreational uses, such as fishing, or provide estimates of the intensity of recreational contact use at individual lakes. User-perception surveys do not ask respondents about possible tradeoffs in water clarity, recreational contact, and fishing quality. The hedonic price studies reported here did not measure other lake attributes or lake conditions, such as fishery productivity or catch rate, and did not acknowledge that improved water clarity might be an indicator of diminished fishing opportunities. Thus, landowner willingness to pay for property on lakes with more productive fisheries may partially account for the unexplained differences in property owners' willingness to pay for properties on different lakes.

2. Conclusions

Most studies were confined to the northern United States and nearly always in areas where water clarity tends to be high (with the exception being one Florida study). Regardless of the region, however, this literature does consistently reflect a general theme: the level of water quality deemed suitable for swimming varies significantly between regions, lakes, and individual users. The lack of information of regional preferences for water clarity and the observed variation in user perceptions within in a region makes it difficult to identify a single water clarity criterion based solely on published literature.

SECTION II-F. DOWNSTREAM EFFECTS OF LAKES AND RESERVOIRS

The U.S. EPA's *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* states, "Before any criterion for any given class of lakes can be adopted, the potential impact on downstream waters must be considered. If the criteria do not provide for the attainment and maintenance of proximal downstream water quality, the criteria in question should be adjusted accordingly" (p. 7-2, U.S. EPA 2000a). Although U.S. EPA recognizes that estuarine and coastal waters eventually receive water discharged from lakes (so are in actuality downstream receiving waters), the agency defines downstream receiving waters for nutrient criteria development purposes as only "those immediately below the lake or reservoir and within a few miles of it" (U.S. EPA 2000a, p. 7-7). Lake and reservoir discharges can impact the temperature, flow, water quality, and biota of downstream receiving waters (in Søballe *et al*. 1992: Young *et al*. 1972; Ward 1976; Ward and Standford 1979, 1981).

Outflows from natural lakes occur from the surface and commonly serve as the headwaters of streams. Most contribute to small streams, but some serve as headwaters for large rivers. For example, Lake Itasca in Minnesota contributes to the headwaters of the Mississippi River (Thornton 1990a). Reservoirs are usually located in river reaches further downstream. Outflows from reservoirs can be located anywhere from the top to the bottom of the dam. Some dams have multilevel outlets so that dam operators can choose from which depth to release water. Waters released from the hypolimnion of stratified reservoirs tend to be cooler, less-oxygenated, and carry more nutrients and solid particles than those withdrawn from the epilimnion.

Primarily because of their position in the watershed and potential for the release of hypolimnion waters, reservoirs (rather than natural lakes) tend to have a greater impact on the water quality of the receiving river. The amount of water, timing of the discharge, and depth of the release influence the effect of a reservoir on downstream waters. Dam releases tend to lessen the seasonal fluctuations in downstream water levels but can increase the daily changes, as often occurs with hydroelectric generating dams (in Søballe *et al*. 1992: Baxter 1977, Ward and Standford 1979).

1. Impacts on Nutrient Levels

Most nutrients stay trapped within natural lakes (Wright 1967 in Kennedy and Walker 1990). Newly constructed reservoirs tend to cause an overall gain in nutrients to downstream waters as nutrients are leached from inundated soils and submerged vegetation decomposes (in Kimmel *et al*. 1990: Baxter 1977, Ostrofsky and Duthie 1980, Grimard and Jones 1982, Kimmel and Groeger 1984). Monitoring above and below established impoundments generally shows that reservoirs reduce the annual loads of nutrients to downstream waters (*e.g*., Heinemann *et al*. 1973; Gloss *et al*. 1980, 1981; Frick *et al*. 1996; Frans *et al*. 2006).

Lake Powell, a reservoir constructed on the Colorado River upstream of Lake Mead, was found to remove about 96% of the TP that once flowed into the upper basin of Lake Mead (Gloss *et al*. 1980, 1981). Lake Red Rock, a reservoir on the Des Moines River, reduced phosphorus levels in downstream waters by more than 75% and resulted in consistently low concentrations in downstream waters even during storm events (Kennedy *et al*. 1981). Likewise, observed

decreases in nutrient concentrations in the Chattahoochee River below Atlanta, Georgia are believed to result from nutrient uptake by phytoplankton and settling in a series of three reservoirs (Frick *et al*. 1996).

Lakes and reservoirs decrease the amount of nutrients to downstream waters through several processes. Phosphorus attached to solid particles may settle out of the water and thus be made unavailable to primary producers in downstream receiving waters. Denitrification that occurs in the surrounding wetlands and in the bottom sediments removes nitrogen from the system. Phytoplankton, macrophytes, and periphyton in lakes and reservoirs take up biologically available forms of nutrients and thus, at least on a temporary basis, keep the nutrients from downstream waters (Frick *et al*. 1996).

Runoff from overland flow tends to have a seasonal component to nutrient input, with snowmelt and spring rains providing pulses of nutrients. Reservoirs temporarily hold this nutrient laden runoff and release it to downstream waters during the following weeks and months. In this way, reservoirs extend the time period of the distribution of nutrients to downstream waters and may continue to release nutrients from spring runoff throughout the growing season (Kimmel *et al*. 1990). The constant input of nutrients from reservoirs can be especially noticeable if the water is discharged from the hypolimnion. This temporal redistribution of nutrients may affect the composition and abundance of algae in rivers downstream of reservoirs.

Stratified reservoirs that discharge from the hypolimnion and have anoxic conditions may contribute phosphorus released from sediments. Other elements and compounds, such as ammonia, hydrogen sulfide, iron, and manganese may also be released. In sufficient quantities, ammonia and hydrogen sulfide are toxic to aquatic organisms. Hydrogen sulfide is also corrosive so can damage dam mechanisms and is associated with odor and taste problems in drinking water. Iron and manganese are undesirable in water supplies because of taste and staining problems (Baker 1996). Although it is more likely that the reservoir (instead of the downstream receiving waters) will serve as a source of water supply, the possible impact of these compounds need to be considered if the receiving waters are used for water supply.

2. Impact on Production Levels

Even if eutrophic lakes and reservoirs provide phosphorus and nitrogen to downstream waters, the supplied nutrients may not lead to excessive algal biomass and impaired conditions in the receiving waters. The nutrient levels may be too low to initiate excessive algal growth in the stream or river community. Søballe and Kimmel (1987) found the ratio of algal counts per unit phosphorus to be highest in natural lakes, intermediate in reservoirs, and lowest in rivers. The authors, however, also found that natural lakes, reservoirs, and rivers did not significantly differ in their productivity per unit of phosphorus when residence times were similar, indicating that the algal response in some river systems or some reaches within a river system could be affected by the supply of nutrients from upstream reservoirs (Søballe and Kimmel 1987).

In some situations, the retention of nutrients within lakes and reservoirs may negatively impact the downstream receiving waters by limiting production. For example, Libby Dam on the Kootenai River in Idaho, the second largest tributary of the Columbia River, retains nutrients to

the extent that periphytic growth downstream of the reservoir is limited (Snyder *et al*. 2002). Snyder and Minshall (2005) developed an energy budget that indicates low levels of nutrients below Libby Dam may even be linked to food limitations for declining populations of the endangered Kootenai white sturgeon (*Acipenser transmontanus*), particularly during early life-history stages.

Phytoplankton from upstream lakes and reservoirs contribute to the food chains of receiving waters (in Søballe *et al*. 1992: Adams *et al*. 1983). This input of phytoplankton is especially noticeable when discharges occur from the surface (in Kimmel *et al*. 1990: Brook and Rzoska 1954, Talling and Rzoska 1967, Hammerton 1972, Shiel and Walker 1984, Petts 1984). Surface discharges contain mostly living phytoplankton whereas hypolimnion discharges have mainly deceased cells and detritus (in Kimmel *et al.* 1990: Coutant 1963, Cowell 1970, Lind 1971, Stroud and Martin 1973). Algae in streams and rivers either develop from phytoplankton and dislodged periphyton from upstream sources, including upstream lakes and reservoirs, or from phytoplankton that originate within the stream system (riverine phytoplankton) (Hynes 1970). Reservoirs, in particular, may provide a constant supply of algae to downstream waters (in Prygiel and Leitao 1994: Ekman-Ekebom *et al*. 1992, Round 1981, and Köhler 1993).

Whether or not limnetic algae survive and increase in population in downstream receiving waters depends on the conditions of the lake/reservoir under which the algae are adapted, the conditions encountered in the receiving stream/river, and the growing conditions needed by the algae. According to Reynolds and Descy (1996, p. 165), "… as a general rule, obligate limnoplankton entering a river generally tends to decrease downstream …." They qualify this generalization, however, to "exclude species introduced from shallow, well-mixed or well-flushed [lake and reservoir] systems, which tend to be dominated by algae with similar preadaptations" (Reynolds and Descy 1996, p. 165).

Streams and rivers offer a complex and changing environment for phytoplankton. Not only must river phytoplankton contend with obtaining sufficient light and nutrients, they must also contend with the turbulence and downstream flow of the water. In order for phytoplankton populations to grow within a stream reach, the populations must reproduce faster than the current displaces them downstream. Therefore, fast-growing taxa have evolved in river systems (Reynolds 1994). In contrast, a fast growth rate is not required for phytoplankton adapted to lakes. Thus, limnetic phytoplankton with slow growth rates, such as some genera of cyanobacteria, are prevented from reaching bloom conditions when introduced to swift flowing streams and rivers and instead are restricted to slow-moving waters (Köhler 1994, Prygiel and Leitao 1994, Reynolds 1994). Köhler (1994) proposed that limnetic phytoplankton able to thrive under conditions of spring circulation (mixing conditions) are more likely to survive turbulent riverine conditions than are those adapted to stratified lakes and reservoirs.

When lake and reservoir conditions are similar to those of the downstream receiving waters, the limnetic and riverine phytoplankton composition can be quite similar. For example, phytoplankton taxa able to withstand frequent fluctuations in light availability are likely to be successful in both shallow lakes and in rivers because both environments tend to be turbid and turbulent. In fact, phytoplankton compositions within turbid, shallow lakes more closely resemble those in rivers than those in either clear, shallow lakes or deep lakes (Reynolds *et al*.

1994). Likewise, when downstream river conditions resemble lake and reservoir environments, limnetic phytoplankton are more likely to survive in the receiving river. For example, Moss *et al*. (1984) and Prygiel and Leitao (1994) observed that some taxa of cyanobacteria from reservoirs continued to grow under low flow conditions in downstream receiving waters.

3. Impact on Dissolved Oxygen and Temperature Levels

Both additions and depletions of oxygen content in downstream waters have been attributed to discharges from reservoirs:

As an example, cold waters, which hold more oxygen, are released from the bottom of Lake Mead, a deep reservoir formed by the construction of Hoover Dam, and have been found to increase the oxygen concentrations in the upper region of a reservoir (Lake Mohave) located immediately downstream (Priscu *et al*. 1981 in Thornton 1990a). The input of cool water from reservoirs can impact the diversity and composition of the aquatic community in downstream waters. Native fish on the lower Colorado River that are adapted to warm, turbid waters are negatively impacted by the input of cool, clearer water from reservoirs (Baker 1996). Alternatively, sometimes the addition of cooler waters can provide habitat for coolwater species such as trout where none existed previously. In such situations, the support of trout populations would be a benefit if trout fishing is considered a designated use.

More often, it is reported that discharges from the hypolimnion of stratified reservoirs deplete oxygen levels in downstream receiving waters, particularly if the discharge is from a shallow reservoir. For example, almost six miles of the Roanoke River in Virginia have been classified as impaired due to low dissolved oxygen levels because of discharges of low-oxygen waters from the hypolimnion of Kerr Reservoir (VDEQ 2004, 2006). Similarly, more than 15 miles of the Pee Dee River in North Carolina are classified as impaired for not supporting aquatic life because of low dissolved oxygen levels; water released from Norwood Dam is listed as the primary potential source of impairment (NC DENR 2006).

SECTION III — TOWARD DEVELOPING NUTRIENT CRITERIA

SECTION III-A. POSSIBLE VARIABLES FOR DETERMINING NUTRIENT IMPAIRMENT

Indicators of eutrophic conditions can be chemical, biological, or composite. Chemical indicators include concentrations of phosphorus and nitrogen. Biological indicators include measurements of biomass and productivity as well as biotic indices based on species richness, diversity, and other community attributes. Composite indicators usually refer to trophic state indices (TSIs).

This section of the literature review provides general information about some of the most commonly considered variables for use in determining nutrient impairments. U.S. EPA recommends using a combination of both causal (*e.g.*, TP, TN) and response variables (*e.g.*, Chl-*a*, turbidity, DO) to avoid having false positive and false negative overenrichment results. The U.S. EPA's technical guidance offers more information on the parameters described here as well as other potential variables (U.S. EPA 2000a).

1. Phosphorus Concentrations

Section I-B of this document (Nutrient Input and Fate in Lakes and Reservoirs) provides general information about phosphorus as a nutrient and its ecological importance. As an essential and potentially limiting nutrient, phosphorus is an important variable to measure. Water samples collected from lakes and reservoirs are routinely analyzed for the amount of phosphorus. Because phosphorus tends to bind to mineral particles, water quality laboratories often filter samples through a 0.45-micron filter. The phosphorus that passes through the filter is called filterable phosphorus. Filterable phosphorus is often referred to as "soluble" or "dissolved" phosphorus even though the filtrate may contain both dissolved and colloidal (tiny particles in suspension) forms of phosphorus. The part of the sample that cannot pass through the 0.45-micron filter is referred to as particulate phosphorus. These particulate samples may contain mineral materials as well as organic components such as bacteria, algae, zooplankton, particles of plant material, *etc.*

Total phosphorus (TP) measures all the organic and inorganic, filterable and particulate forms of phosphorus. TP is generally measured when describing the phosphorus enrichment level of lakes and reservoirs because most of the phosphorus in the system is in the particulate form and will assumedly be recycled within the water body in a form that is accessible to primary producers (Horne and Goldman 1994, Wetzel 2001). Phosphorus concentrations of water samples taken from lakes and reservoirs are generally reported in units of ppb, µg/L (1 µg/L = 1 ppb), or mg/L.

2. Nitrogen Concentrations

Nitrogen is another essential nutrient that is described in more detail in Section I-B of this review. Nitrogen in water samples can be measured in several different forms, for example:

- nitrate-N = (NO_3-N)
- nitrite-N = (NO_2-N)

- total ammonia-N = ammonia-N (NH_3-N) + ammonium-N (NH_4-N)
- total Kjeldahl nitrogen (TKN) = total ammonia-N + total organic nitrogen
- total nitrogen (TN) = NO_3-N + NO_2-N + TKN

Because these nitrogen species can be converted from one form into other forms, nitrogen in water samples from lakes and reservoirs is usually reported as total nitrogen (TN). Total nitrogen measures all the nitrates, nitrites, total ammonia-N, and total organic nitrogen in the water. Nitrogen measurements from lake and reservoir samples are typically expressed in units of mg/L.

3. Chlorophyll-*a* Concentrations

The biomass of phytoplankton in lakes and reservoirs is often estimated by measuring the amount of chlorophyll-*a* (Chl-*a*), the predominant green pigment used in photosynthesis. Chl-*a* can be determined from a sample of phytoplankton collected from the water column. To determine the amount of Chl-*a*, the chlorophyll is extracted from the cells with a solvent such as acetone. The Chl-*a* value is then measured by such means as spectrophotometry, fluorometry, or high pressure liquid chromatography (HPLC) (APHA 1998). Chlorophyll-*a* concentrations from water samples taken from lakes and reservoirs are generally reported in units of ppb, µg/L, or mg/m^3 (1 ppb = 1µg/L = 1 mg/m^3).

U.S. EPA cautions that Chl-*a* data derived from the different methodologies are not interchangeable (U.S. EPA 2000b-h, 2001a-e). Spectrophotometry measures the amount of light absorbance at specific wavelengths. One method of spectrophotometric analysis relies on trichromatic equations. U.S. EPA does not recommend the use of Chl-*a* values derived by trichromatic equations unless no other data exist (U.S. EPA 2000b-h, 2001a-e). Fluorometry measures the amount of light emitted at a particular wavelength when exposed to light at a different wavelength. The presence of other chlorophyll pigments (*e.g.*, pheophytin) can interfere with the Chl-*a* measurement using either the spectrophotometric or fluorometric methods. For this reason, U.S. EPA prefers data from methods that also incorporate an acid correction treatment (U.S. EPA 2000b-h, 2001a-e). *Standard Methods for the Examination of Water and Wastewater* (APHA 1998), however, does not recommend the acidification step for freshwaters when using the fluorometric technique if pheopigments (Chl-*b*) are also present. Although HPLC accurately separates the pigments based on physical characteristics, it is an expensive and time-consuming method so is not used as often as the spectrophotometric and fluorometric methods (NC WRRI 2001). Furthermore, for the purpose of estimating biomass, the accuracy provided by HPLC is not necessary (U.S. EPA 2000a).

Some experts suggest recording total chlorophyll pigments because all current methods of measuring chlorophyll-*a* concentrations ignore some interferences. Carlson and Simpson (1996) state: "It is strongly recommended that the total chlorophyll pigment be reported in addition to chlorophyll a. This value, although flawed by interferences by other chlorophylls, phaeo-pigments, as well as a number of other possible interferences, is the only value that remains fairly independent of chlorophyll methodology. Therefore, it is the only measurement that provides historical consistency. Chlorophyll a methodologies have changed over the past 25 years, and with each change, the previous chlorophyll estimates became obsolete and non-

comparable to the new methods. If everyone had reported total chlorophyll, at least there would be one consistent value that would allow comparison. In a monitoring program, where historical data consistency is absolutely necessary, this value should be reported."

4. Transparency Measurements

Light entering a lake or reservoir decreases with depth because it is absorbed or scattered by particles in the water or the water itself. The transparency of the water is therefore affected by the water itself, colored matter, and inorganic and organic (including algae) solids. As algal abundance, color, and/or suspended solids increase, transparency decreases. U.S. EPA suggests a measurement of summer transparency to estimate eutrophication and specifically mentions the use of Secchi depth measurements to indicate the trophic state of lakes and reservoirs (U.S. EPA 2000a-h, 2001a-e). A standard Secchi disk is 20 cm in diameter and is either all white or has alternating black and white quadrants. There are various techniques to measure transparency with a Secchi disk. In general, the disk is lowered into the water of a lake or reservoir until it can no longer be seen. The depth at which the disk cannot be seen indicates the transparency of the water. Some suggest that Secchi depth (SD) should only be used as a simple visual index of the clarity of a body of water (Preisendorfer 1986 in Carlson and Simpson 1996). Others have found strong relationships between SD, Chl-*a* values, and TP concentrations so suggest the use of Secchi depth as a surrogate measure of algal chlorophyll or algal biomass (Carlson 1977).

5. Trophic State Indices

Trophic state indices (TSIs) describe the trophic status of lakes and reservoirs. In 1977, Robert Carlson published a TSI that is based on Secchi depth as a means of characterizing algal biomass. Carlson's TSI is based on the assumption that, in the absence of turbidity and colored materials in water, Secchi depth can estimate the algal biomass in natural waters.

By using empirically derived interrelationships between Secchi depth, total phosphorus, and chlorophyll-*a* values, Carlson derived equations to estimate the same index value from either Secchi depth, TP, and/or Chl-*a*. The TSI ratings are based on the following equations, as defined by Carlson (1977) for northern temperate lakes:

$$TSI(SD) = 10(6 - (\ln SD / \ln 2))$$

$$TSI(TP) = 10(6 - ((\ln 48 / TP) / \ln 2))$$

$$TSI(CA) = 10(6 - ((2.04 - 0.68 \ln CA) / \ln 2))$$

where SD = Secchi depth (m), TP = total phosphorus (ppb), and CA = chlorophyll-*a* (ppb). If a lake or reservoir reacts as predicted by Carlson's functions, the trophic state of the lake would be similar no matter if determined from TP, Chl-*a* , or Secchi depth. Likewise, any of the three parameters could be used to estimate the other two (Carlson 1977).

Carlson's trophic index is basically a linear transformation of Secchi depth. The obtained range of values can be transformed into a consistent scale (Figure III-1). Most lakes in the world fall into the range from 0 to 100. Each 10 unit increase (10, 20, 30, *etc.*), represents a halving of the Secchi depth, a doubling of the TP, and about a 2.8 fold increase in Chl-*a*. Thus, a TSI of close to zero represents an ultra-oligotrophic water body, whereas a TSI that approaches 100 represents a hypereutrophic status.

Carlson's Trophic State Index

TSI < 30 Classic Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion, salmonid fisheries in deep lakes.

TSI 30 - 40 Deeper lakes still exhibit classical oligotrophy, but some shallower lakes will become anoxic in the hypolimnion during the summer.

TSI 40 - 50 Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.

TSI 50 - 60 Lower boundary of classical eutrophy: Decreased transparency, anoxic hypolimnia during the summer, macrophyte problems evident, warm-water fisheries only.

TSI 60 - 70 Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.

TSI 70 - 80 Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration. Often would be classified as hypereutrophic.

TSI > 80 Algal scums, summer fish kills, few macrophytes, dominance of rough fish.

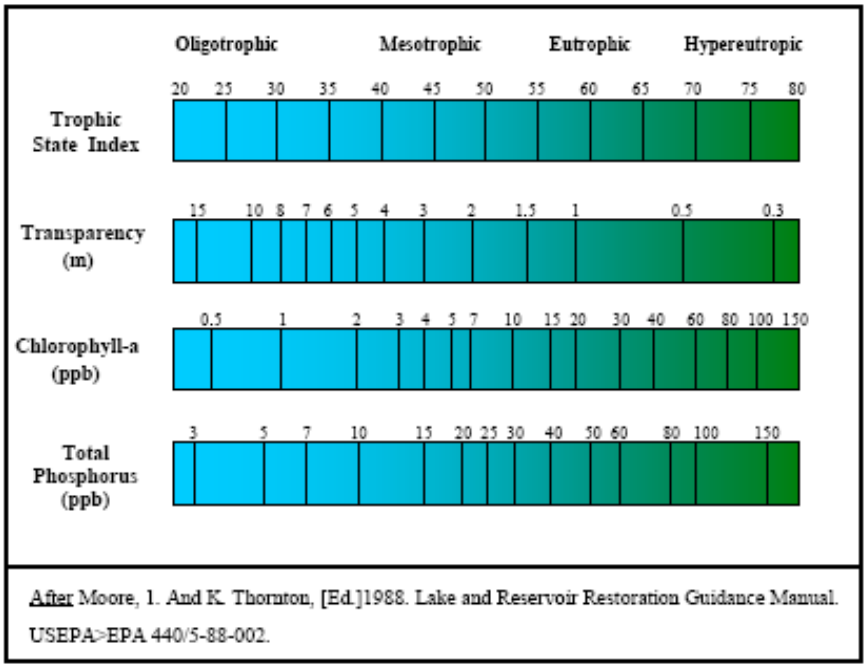

Figure III-1. Carlson's Trophic State Index
(Source: Heiskary and Wilson 2005 [referencing R.E. Carlson; Moore and Thornton 1988]).

Suggested TSI limits to classical trophic state terminology are:

Ultra-oligotrophy	(0-20)
Oligotrophy	(20-40)
Mesotrophy	(40-50)
Eutrophy	(50-70)
Hypereutrophy	(>70)

A TSI value of 60 or greater indicates average eutrophic conditions and corresponds to a Secchi depth of 1 meter, a chlorophyll-*a* value of 20 ppb (or µg/L), and a TP concentration of 48 ppb (or µg/L) (Figure III-1.). Carlson and Simpson (1996) predict that a north temperate lake with a TSI of 60 would experience taste and odor problems if used for drinking water and would possibly have nuisance macrophytes, algal scums, and low transparency that could discourage swimming and boating.

According to Carlson (1977), the TSI is a simple approach based from easily obtained data with known relationships. The TSI is also a good means to portray scientific information in a way that can be understood by the general public.

The Carlson index will not work if phytoplankton are limited by a nutrient other than phosphorus. For example, Carlson's TSI is not applicable in lakes that are limited by nitrogen. Likewise, Carlson's TSI will not work for lakes and reservoirs where Secchi depth is significantly influenced by non-algal turbidity and/or dissolved water color (Horne and Goldman 1994).

Another problem with using Carlson's TSI to express nutrient criteria is its inability to account for spatial and temporal differences within the water body. Sediment-related non-algal turbidity varies spatially across the water body and temporally in response to weather conditions and seasonal cycles. For example, in reservoirs the most turbid region is likely to be in the upper channel. The TSI would register the increased turbidity as representing a higher trophic state, but this is in not generally the most productive region.

Other TSIs besides Carlson's have also been developed. For example, Kratzer and Brezonik (1981), Huber *et al.* (1982), and others have developed nitrogen-based TSIs for use in N-limited lakes and reservoirs. These TSIs can be used when the N:P ratio (wt:wt) is <10, which indicates N limitation. Brezonik (1984) and Cooke *et al.* (1993) (in Baker [1996]) have reviewed indices based on other variables, including those that are based on macrophytes and hypolimnetic dissolved oxygen.

6. Dissolved Oxygen Concentrations

Because dissolved oxygen levels are influenced by changes in the trophic state of lakes and reservoirs, DO can be an important variable for determining nutrient-impaired waters. Whereas chlorophyll-*a* concentrations and Secchi depth are primary response variables because increases in nutrient concentrations lead directly to greater algal growth and decreased water transparency, DO is a secondary response variable (U.S. EPA 2000a). Excess nutrients cause an increase in algal growth, which then leads to lower DO concentrations.

Oxygen primarily dissolves in water from either the atmosphere or as a byproduct of photosynthesis. The amount of oxygen that freshwaters can hold depends on the water temperature and pressure. For example, colder waters are able to hold more DO. Under certain circumstances, the water can become supersaturated with oxygen, meaning that it holds more than 100% of the amount of oxygen than could be dissolved under normal circumstances at that temperature and pressure. Supersaturation can occur as a result of photosynthesis by excessive

amounts of primary production. Supersaturation of lakes and reservoirs (or the epilimnion of stratified waters) on sunny, warm days may indicate excessive photosynthetic activity and thus eutrophic conditions.

The vertical distribution of oxygen concentrations can be used as a rough estimate of trophic state in natural lakes. In summer, within stratified oligotrophic lakes, an *orthograde* oxygen curve is typically observed whereby the epilimnion has lower oxygen concentrations than the hypolimnion because the warmer, surface waters hold less oxygen than the cooler, deeper waters of the hypolimnion. In these oligotrophic lakes, the water column is well oxygenated throughout. In contrast, eutrophic stratified lakes in summer tend to display a *clinograde* oxygen curve, whereby oxygen levels are higher in the epilimnion than in the hypolimnion. Clinograde oxygen curves indicate consumption of oxygen in the hypolimnion through such processes as decay of organic matter from deceased phytoplankton and macrophytes. Therefore, the amount of oxygen deficit in the hypolimnion of natural lakes can indicate the amount of primary production in the epilimnion (Cole 1994).

The use of vertical DO concentrations to indicate trophic conditions as used for natural lakes, however, is not applicable to reservoirs because hypolimnetic DO depletion is common in both oligotrophic and eutrophic reservoirs. Compared to natural lakes, reservoirs have more complex oxygen distribution patterns. The change in depth and width along the length of a reservoir results in longitudinal differences in the amount of DO available to meet oxygen demands. Furthermore, changes in morphology and water velocity along the length of reservoirs cause longitudinal gradients in many other factors (*e.g.*, primary production, sedimentation, hypolimnetic temperature) that impact oxygen demand (Cole and Hannan 1990). Oxygen depletion in reservoirs usually begins in the hypolimnetic waters of the thalweg (lowest part of the reservoir, generally along the length of the old streambed) within the transition zone and expands outward and upward (Cole and Hannan 1990).

Maintaining an adequate DO concentration in all regions of lakes and reservoirs at all times is important because aquatic organisms require DO. During turnover, the bottom waters are transported to the surface where they are aerated. Thus, during mixing periods, oxygenated conditions are most likely to exist throughout the entire water column. In contrast during stratified periods, such as in summer, the two layers are separate. DO deficiencies are most likely in the hypolimnion because (1) the water in the hypolimnion is isolated from the atmosphere, (2) the levels of light in the hypolimnion are not sufficient for photosynthesis so oxygen as a byproduct of photosynthesis is not available, and (3) the hypolimnion is the primary region of decomposition so bacteria that utilize oxygen are active and deplete the supply of dissolved oxygen.

As a lake or reservoir becomes eutrophic, the rate of oxygen deficiency in the hypolimnion increases. Under eutrophic conditions, more organic materials settle into the hypolimnion and decompose. Partially decomposed matter also accumulates in sediments where it decomposes in subsequent years. The decomposition of settled material and subsequent decrease of hypolimnion DO may occur prior to noticeable changes of the algal community of the epilimnion. Thus, the oxygen concentration of the hypolimnion and its rate of depletion may be

potentially useful in identifying eutrophic conditions (Carlson and Simpson 1996, U.S. EPA 2000a).

Care must be taken in using oxygen depletion in the hypolimnion to indicate changes in trophic state because many other factors contribute to DO levels including the morphometry of the water body and the size of the hypolimnion relative to the epilimnion. For instance, the size of the hypolimnion is so important that oxygen depletion rates are typically indexed to the hypolimnion surface area (referred to as the *areal hypolimnetic oxygen deficit*) (Hutchison 1957 in U.S. EPA 2000a). The temperature of the water, dissolved color in the water, and other factors also control DO levels. For example, oligotrophic or mesotrophic lakes and reservoirs in warmer environments could be considered eutrophic if based on only oxygen deficits.

SECTION III-B. MANAGEMENT ISSUES

When implementing nutrient criteria, it will be important to recognize the management history of individual lakes or reservoirs. Depending on the parameters analyzed (*e.g.*, nutrient concentrations, Chl-*a* levels, oxygen profiles, *etc.*), certain management practices could affect monitoring results. For example, some lakes and reservoirs used to grow fish for stocking or commercial harvest add fertilizer to encourage primary production and strengthen the base of the food web. Obviously, because fertilizers contain nutrients, nutrient levels and other parameters, such as Chl-*a*, would likely be affected by the addition of fertilizers.

Low hypolimnetic DO levels, as a consequence of cultural eutrophication, are of concern to lake and reservoir managers because such waters provide poor fish habitat and release nutrients from the sediment. For example, under low hypolimnetic oxygen conditions, hydrogen sulfide, manganese, and iron — substances associated with drinking water odor, taste, and staining issues — can be released from bottom sediments and drawn into water supply treatment systems. The managers of lakes and reservoirs, therefore, often provide some means to increase oxygen levels (Cooke and Carlson 1989, Horne and Goldman 1994).

Many water supply plants use one of several methods to increase oxygen concentrations in the hypolimnion of their water supply lakes and reservoirs. Methods to increase DO in managed lakes and reservoirs include the addition of calcium nitrate, artificial circulation, side stream oxygenation, and oxygenation of the hypolimnion (Horne and Goldman 1994).

- The addition of calcium nitrate, as described in Section II-B (Impoundment Issues that Affect Nutrients — Internal Loading) oxidizes, precipitates, and immobilizes phosphates, iron, and hydrogen sulfide (Horne and Goldman 1994).
- Artificial circulation vertically mixes the water with paddles, water pumps, or injected air (Pastorok *et al*. 1981 in Baker 1996). In addition to increasing DO levels, this method has been shown to cause a shift in the algal dominance from cyanobacteria (blue-green algae) to green algae (Cooke and Pastorok *et al*. 1981 in Baker 1996).
- With side stream oxygenation, small quantities of water from the hypolimnion are withdrawn, supersaturated with oxygen, and returned to the hypolimnion.
- Studies documenting the effects of hypolimnetic oxygenation have been reviewed by Fast and Lorenzen (1976), Pastorok *et al*. (1982), McQueen and Lean (1986), and Beutel and Horne (1999). In their review, Beutel and Horne (1999) reported that as a result of

hypolimnion oxygenation, average hypolimnetic DO concentrations were maintained at greater than 4 mg/L in all cases. Furthermore, hypolimnetic concentrations of dissolved phosphorus, ammonia, manganese, and hydrogen sulfide were reduced by 50 – 100 percent. Likewise McQueen and Lean (1986) found that for generally all installations, iron, manganese, and hydrogen sulfide levels decreased following hypolimnetic oxygenation (Appendix C in Zipper *et al*. 2005).

Biological manipulations of lakes and reservoirs need to be considered when developing and implementing nutrient criteria. If using Chl-*a* concentrations as a criterion, it will be important to know which lakes and reservoirs have been chemically treated and how. For instance, many water supply plants control algae by adding copper sulfate. In sufficient doses, cupric ions kill algae, which would then reduce the amount of Chl-*a* in water samples taken from treated lakes and reservoirs (Horne and Goldman 1994). Methods used to control nuisance levels of macrophytes in shallow lakes and reservoirs include the harvesting of plants, dredging of sediment, lowering of water, and stocking of grass carp (Horne and Goldman 1994, Baker 1996). Thus, if macrophytic coverage is used as part of the criteria, it would be necessary to know whether or not any of these or other management treatments had been used.

SECTION III-C. VARIOUS APPROACHES TO DEVELOPING NUTRIENT CRITERIA

1. U.S. EPA's Approach

A group of national experts working with U.S. EPA in addressing nutrient criteria development issues recommended that U.S. EPA "not develop single criteria values for phosphorus or nitrogen applicable to all water bodies and regions of the country. Rather, the experts recommended that EPA put a premium on regionalization, develop guidance (assessment tools and control measures) for specific water bodies and ecological regions across the country, and use reference conditions (conditions that reflect pristine or minimally impacted waters) as a basis for developing nutrient criteria" (U.S. EPA 2000b-h, 2001a-e, p. 1).

For the contiguous United States, therefore, U.S. EPA developed 14 aggregate nutrient ecoregions. Ecoregions represent "regions of relative homogeneity in ecological systems; they depict areas within which the mosaic of ecosystem components (biotic and abiotic as well as terrestrial and aquatic) is different than adjacent areas in a holistic sense" (U.S. EPA 2000b-h, 2001a-e, p. 3). This aggregate ecoregion system was developed by combining U.S. EPA's level III ecoregions in such a way as to represent similarities in geology, soils, climate, hydrology, vegetation, and wildlife. These components influence the natural levels of nutrients in lakes and reservoirs and the movement of nutrients through these systems. The large-scale aggregate ecoregions were used by U.S. EPA to develop guidance nutrient levels. By lumping data from several level III ecoregions, however, variability within the aggregate nutrient ecoregion was high. Thus, U.S. EPA "recommends that States and Tribes develop nutrient criteria at the level III ecoregional scale and at the waterbody class scale where those data are readily available" (U.S. EPA 2000b-h, 2001a-e, p. 3).

The guidance manual developed by U.S. EPA, *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (U.S. EPA 2000a), describes three general approaches that can be used to establish reference conditions (U.S. EPA 2000a):

- data collection from lakes that represent reference conditions;
- paleolimnological reconstruction of past conditions;
- model-based reference conditions from related data sets or knowledge.

The reference conditions are to represent "the least impacted conditions or what is considered to be the most attainable conditions. While the reference conditions themselves are not specifically established as criteria, they help to set the upper bounds of what can be considered the most natural and attainable lake conditions for a specific region" (U.S. EPA 2000a, p. 6-1).

Following one of the methods outlined in the manual (data collection from lakes that represent reference conditions), U.S. EPA developed ambient water quality criteria recommendations for TP, TN, Chl-*a*, and Secchi depth for each of the 14 aggregate nutrient ecoregions (U.S. EPA 2000b-h, 2001a-e, Table III-1). For these candidate criteria, U.S. EPA used frequency distributions of data collected from all lakes and reservoirs within the aggregate ecoregion that met U.S. EPA's quality assurance/quality control criteria.

Table III-1. Lake and reservoir recommended U.S. EPA criteria for each of the aggregate nutrient ecoregions (Agg Ecor) for total phosphorus, total nitrogen, chlorophyll-*a*, and Secchi depth.

Parameter	Agg Ecor II	Agg Ecor III	Agg Ecor IV	Agg Ecor V	Agg Ecor VI	Agg Ecor VII	Agg Ecor VIII	Agg Ecor IX	Agg Ecor XI	Agg Ecor XII	Agg Ecor XIII	Agg Ecor XIV
TP µg/L	8.75	17.00	20.00	33.00	37.5	14.75	8.00	20.00	8.00	10.00	17.50	8.00
TN mg/L	0.10	0.40	0.44	0.56	0.78	0.66	0.24	0.36	0.46	0.52	1.27	0.32
Chl *a* µg/L	1.90	3.40	2.00 S	2.30 S	8.59 S	2.63	2.43	4.93	2.79 S	2.60	12.35 T	2.90
Secchi (m)	4.50	2.70	2.00	1.30	1.36	3.33	4.93	1.53	2.86	2.10	0.79	4.50

Chl-*a* is measured by Fluorometric method unless specified. S is for Spectrophotometric, and T is for Trichromatic method.

A reference condition for the aggregate nutrient ecoregion was inferred by U.S. EPA using the following process:

(1) Within a given ecoregion, each water body was represented by four seasonal medians, a median value for each season (winter, spring, summer, fall) (Figure III-2).

(2) A frequency distribution of the median values for each season was plotted, resulting in four distribution graphs (winter, spring, summer, fall) for the ecoregion (Figure III-3, U.S. EPA 2000b-h, 2001a-e). For TP, TN, and chlorophyll-*a* concentrations, the data were ordered from low values to high values because high levels of these parameters are associated with low water quality. In contrast, the data were ordered from high values to low values for Secchi depth because high Secchi disk measurements are associated with

good water quality conditions and low Secchi depth readings generally indicate poor water quality conditions (U.S. EPA 2000a)

(3) The reference condition for the ecoregion was then established as the median value of the seasonal 25th percentiles (Figure III-3, U.S. EPA 2000a).

U.S. EPA used the 25th percentile of all lakes and reservoirs because several studies indicate this boundary approximates the 75th percentile (or upper 25th percentile) of reference water bodies, as illustrated in Figure III-4 (U.S. EPA 2000a). The agency chose the 75th percentile of reference water bodies for criteria setting because it is "likely associated with minimally impacted conditions, will be protective of designated uses, and provides management flexibility" (U.S. EPA 2000b-h, 2001a-e). U.S. EPA states that the use of specific percentiles is only a suggestion and stresses that the main reason to choose a particular threshold should be based on the actual distribution of data for the given region (U.S. EPA 2000a).

U.S. EPA recommends using its suggested reference conditions as only a guide or "first step" in setting nutrient criteria. States and authorized tribes are encouraged to select reference conditions at smaller geographic scales and refine their criteria through the use of models and published literature and in consideration of downstream effects and expert judgment (U.S. EPA 2000b-h, 2001a-e). If states and authorized tribes do not develop criteria that can be approved by U.S. EPA, the ecoregion criteria developed by U.S. EPA will become the default standard.

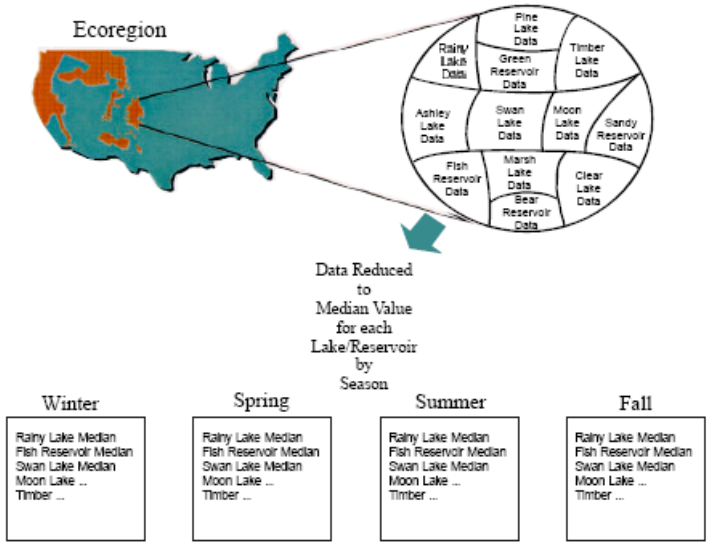

Figure III-2. Illustration of data reduction process for lake data. (Source: U.S. EPA 2000b-h, 2001a-e)

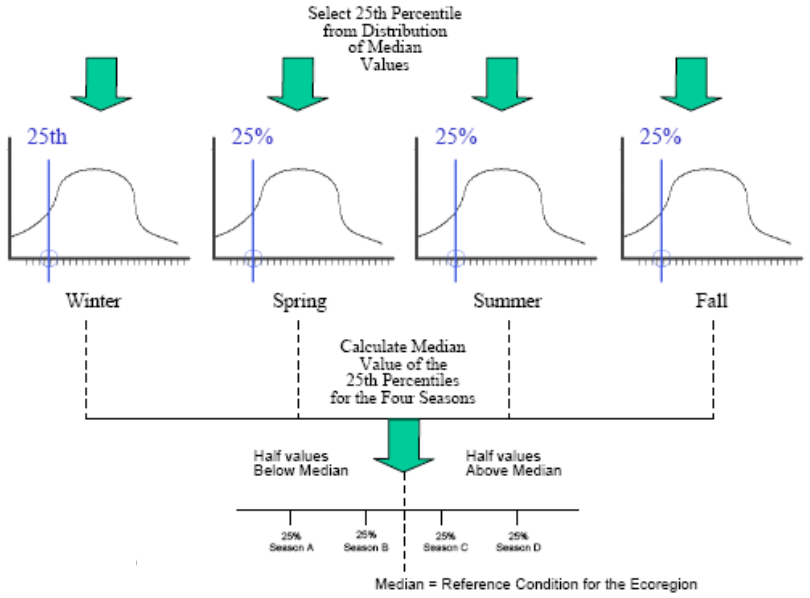

Figure III-3. Illustration of reference condition calculation. (Source: U.S. EPA 2000b-h, 2001a-e)

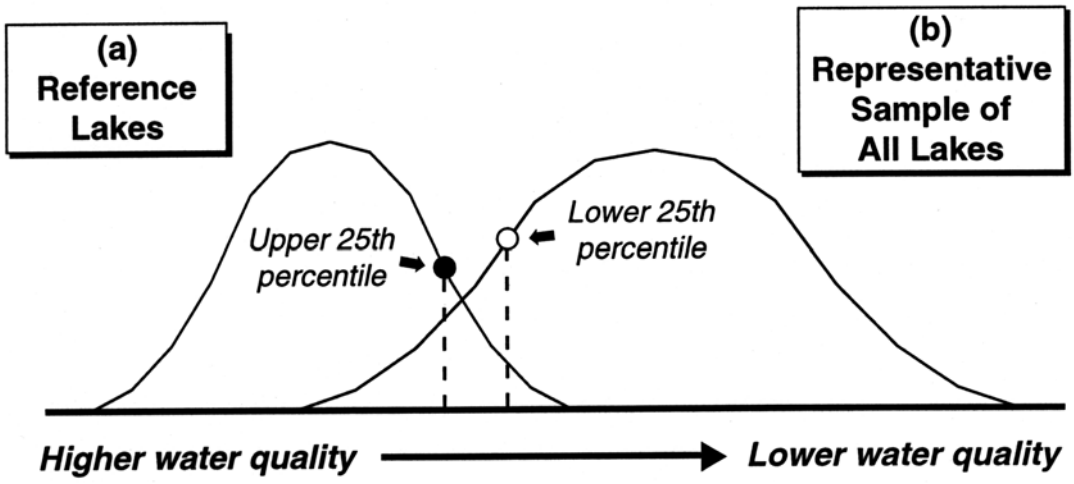

Figure III-4. Two approaches for establishing a reference condition value. Note: Percentiles are based on order statistics, statistics derived from ordering data from low to high or high to low. In the case of TP, TN, and chlorophyll *a*, higher concentrations of the variable result in lower water quality. Consequently, the scale presented above is ordered from low to high. A similar analysis of Secchi depth, however, would require ordering the data from high to low because higher Secchi disk readings are associated with higher water quality (Source: U.S. EPA 2000a, page 6-8).

2. Minnesota's Approach

Minnesota established TP guidance criteria for lakes in 1988 to protect recreational uses and aquatic life uses (specifically, coldwater fisheries) (Heiskary and Wilson 1988). New criteria are being proposed (as of August 2007). The new nutrient standards are expected to give the Minnesota Pollution Control Agency (MPCA) greater legal authority and will likely serve as a basis for setting phosphorus limits for point sources. Additionally, these new standards could help local governments and decision makers reach consensus concerning lake management issues (MPCA 2007).

a. Designated Uses to Protect

Lakes and reservoirs in Minnesota serve multiple purposes so the proposed nutrient criteria will need to protect various designated uses. Lakes and reservoirs in Minnesota are classified in Minnesota's Rules (Chapter 7050) as either "Class 2 waters" (Class 2A and Class 2B) or "Class 7 waters." Designated uses of Class 2 waters include aquatic life support and recreation. Class 7 waters are designated as limited resource value waters. All lakes in Minnesota (both Class 2 and Class 7) are to protect industrial, agricultural, navigational, aesthetic, and other uses. Within Class 2, some lakes are listed as "Class 2A waters." The designated uses of Class 2A waters include coldwater fisheries, primary contact (includes activities where ingestion of water is likely, ***e.g.***, swimming, waterskiing), and drinking water supply. Most lakes in Minnesota, however, are classified as "Class 2B waters," meaning their designated uses specifically include: coolwater and warmwater fisheries and primary contact (not water supply) (Heiskary and Wilson 2005, MPCA 2007).

Because lakes serve several purposes, MPCA selected the "most sensitive sub-use" for deriving lake nutrient criteria. The most sensitive sub-use is defined as "that use (or uses) which can be affected or even lost as a result of an increase in the trophic status of the lake" (Heiskary and Wilson 2005, p. vii). For example, primary contact would be a more restrictive recreational use than secondary contact because algal blooms and excessive growth of macrophytes are more likely to limit swimming as opposed to preventing boating, fishing, and wading. Likewise, coldwater fisheries are more sensitive than warmwater fisheries because coldwater fish can be restricted to the colder bottom waters of lakes during summer. Consequently, these fish require sufficient dissolved oxygen levels in the lower parts of inhabited lakes where the maintenance of adequate oxygen levels can be particularly difficult during lake stratification.

b. Databases

MPCA relied heavily on previous research findings related to developing TP guidance criteria (Heiskary and Wilson 1988) and also followed closely the process proposed in U.S. EPA's *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* for developing nutrient criteria (Figure III-5, U.S. EPA 2000a). Several databases were created and used to evaluate ecoregions in Minnesota and to classify lakes and reservoirs within the state. The databases included data about watershed characteristics, lake morphometry, lake ecology (fish and macrophyte requirements), U.S. EPA's aggregate nutrient ecoregion lake conditions for the region, Minnesota's reference lake conditions, Minnesota's water quality lake assessment conditions, user perceptions, historic reconstructions of lake water quality, and other information (Heiskary and Wilson 2005).

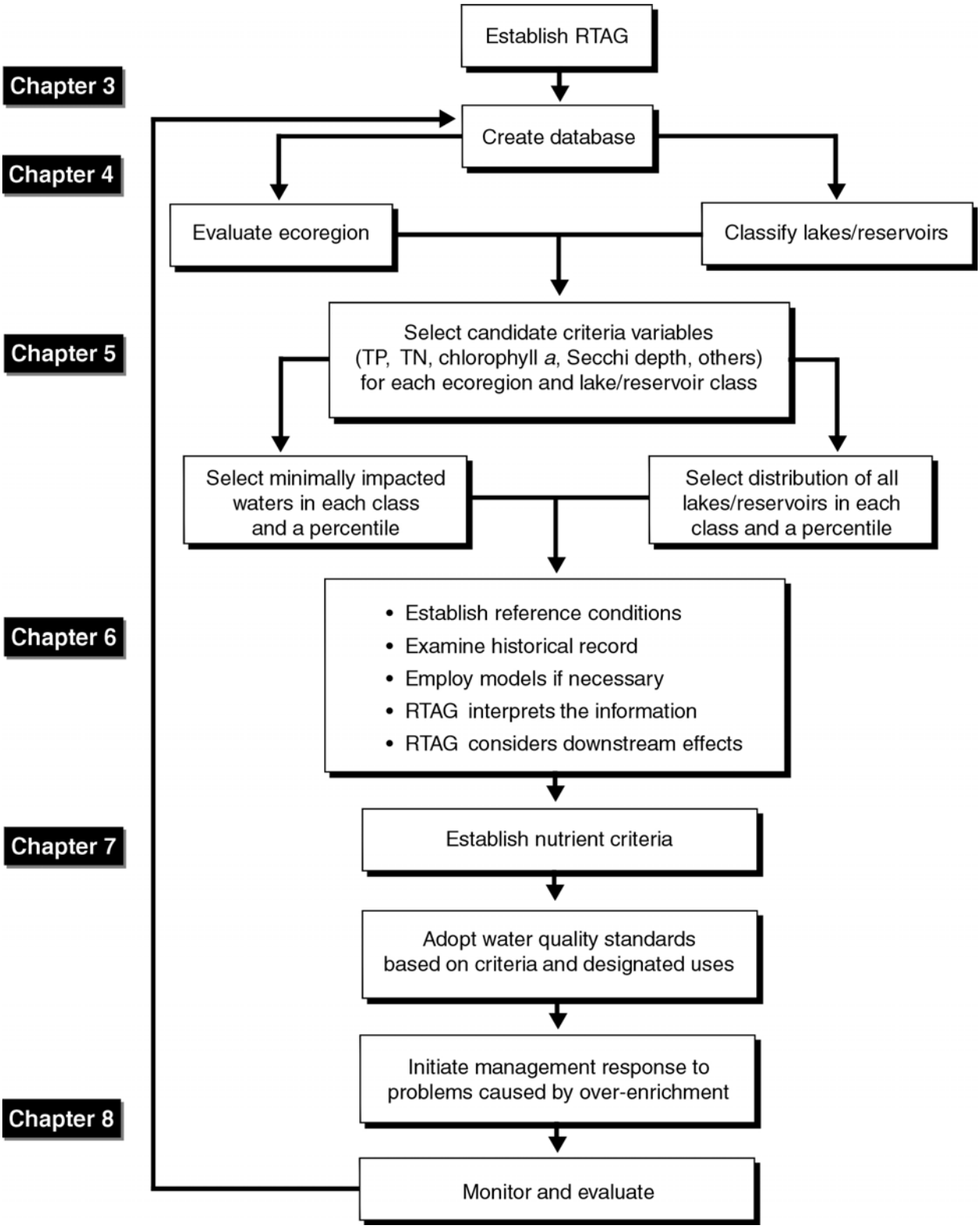

Figure III-5. Flowchart of the nutrient criteria development process. (Source: U.S. EPA 2000a).

For example, the "reference lake database" consisted of 90 lakes that are considered to be minimally impacted by both point and nonpoint sources of pollution. The database did not include lakes located in large urban settings or those that receive either effluent from point sources or runoff from large feedlots. The reference lakes were sampled three or four times during the summer for numerous years (Heiskary and Wilson 2005).

c. Ecoregions

Minnesota has a diversity of landscapes, from forested lands in the north to prairie and agricultural lands in the south. MPCA divided Minnesota into seven distinct ecoregions with plans to develop ecoregion-specific nutrient criteria, using the ecoregions established by Omernik (1987). Four ecoregions — Northern Lakes and Forests (NLF), Central Hardwood Forests (CHF), Western Corn Belt Plains (WCP), Northern Glaciated Plains (NGP) — contain 98 percent of the lakes in the state. A brief description of the lake characteristics of these four ecoregions obtained from reference lake data and Minnesota Department of Natural Resources (MDNR) fishery classification data follows:

- Northern Lakes and Forests (NLF) ecoregion
  - -- moderately deep lakes
  - -- forest and wetlands land use
  - -- TN:TP ratio suggests P-limited
  - -- TSS concentrations tend to be very low
  - -- mesotrophic to mildly eutrophic
  - -- fish ecology: bass-panfish, bass-panfish-walleye, soft water walleye (some trout)
  - -- fish management: bass-panfish-walleye
- Central Hardwood Forests (CHF) ecoregion
  - -- moderately deep lakes (but also has a high percentage of shallow lakes)
  - -- no single land use dominates
  - -- TN:TP ratio suggests P-limited
  - -- TSS concentrations tend to be low
  - -- eutrophic
  - -- fish ecology: bass-panfish, winterkill-roughfish
  - -- fish management: centrarchid (largemouth bass) and walleye
- Western Corn Belt Plains (WCP) ecoregion
  - -- shallow lakes
  - -- agricultural land use
  - -- TN:TP ratio suggests some P-limited, others possibly co-limited by P and N
  - -- TSS concentrations tend to be high in shallow lakes
  - -- eutrophic to hypereutrophic
  - -- fish ecology: winterkill-roughfish (some bass-panfish, bass-panfish-walleye-bullhead)
  - -- fish management: centrarchid-walleye (largemouth bass-walleye)
- Northern Glaciated Plains (NGP) ecoregion
  - -- shallow lakes
  - -- agricultural land use
  - -- TN:TP ratio suggests possibly co-limited by P and N
  - -- TSS concentrations tend to be high

-- hypereutrophic
-- fish ecology: winterkill-roughfish (some bass-panfish, bass-panfish-walleye-bullhead)
-- fish management: warmwater game fish

The other three ecoregions in Minnesota — Red River Valley (RRV), Paleozoic Plateau (PP), and Northern Minnesota Wetlands (NMW) — have comparatively small amounts of lake data. Thus, nutrient criteria developed for adjacent ecoregions could be used. For instance, the criteria developed for the ecoregion or ecoregions within the same U.S. EPA aggregate nutrient ecoregion could be used (see Table III-2). Alternatively, site-specific criteria could be developed for lakes in these three ecoregions.

Table III-2. Ecoregions in Minnesota as related to U.S. EPA's aggregate nutrient ecoregions.

U.S. EPA Aggregate Nutrient Ecoregions	Minnesota Ecoregions (based on work of Omernik 1987)		
VI	Western Corn Belt Plains	Northern Glaciated Plains	Red River Valley
VII	Central Hardwood Forests	Paleozoic Plateau	
VIII	Northern Lakes and Forests	Northern Minnesota Wetlands	

d. Lakes/Reservoirs Classification

As a part of the nutrient criteria development process, MPCA classified the lakes by three main ways. The first distinction occurs between natural lakes and reservoirs. Because Minnesota has few constructed reservoirs, MPCA proposed that site-specific criteria be developed for reservoirs (Heiskary and Wilson 2005). The remainder of this nutrient development description for Minnesota, therefore, focuses specifically on natural lakes.

The second lake classification separates lakes by use designation (*e.g.*, Class 2A, Class 2B, Class 7). This category is particularly important for lakes that serve special uses. For example, owing to increases in drinking water treatment and costs associated with increased levels of nutrients and resulting algal populations, MPCA proposed that public water supply lakes receive their own distinct classification. Likewise, lakes that support sensitive fisheries were given special classifications. Minnesota's lakes that are able to support natural populations of lake trout (*Salvelinus namaycush*) are classified as "lake trout lakes." In Minnesota, lakes stocked with the following trout species: brook, brown, and rainbow as well as splake (hybrids of brook trout and lake trout) are classified as "stream trout lakes."

The third classification concerns lake depth, which influences the ability of lakes to assimilate nutrients, recycle nutrients, and determine if macrophytes or phytoplankton dominate. MPCA

defines lakes with maximum depths of 15 feet or less or those with littoral areas covering 80 percent of more of the lake as "shallow lakes."

As part of the ecoregion-nutrient criteria being proposed, MPCA identified the most sensitive sub-use for water body type (Table III-3). The most sensitive sub-use for lake trout lakes and stream trout lakes includes support of the sensitive aquatic community. For shallow lakes, protection of the aquatic community is the most sensitive sub-use, whereas for lakes greater than 15 feet in depth, the recreational use is the most sensitive sub-use.

Table III-3. Subcategories of beneficial uses within the aquatic life and recreation uses that the nutrient criteria are designed to protect (Source: Heiskary and Wilson 2005).

Waterbody type	**Uses. The more "sensitive" use, which is the primary basis for the proposed standard, is listed as number 1. Other uses follow.**
Lake trout lakes	1. Protection of sensitive aquatic community. Specifically, maintenance of adequate dissolved oxygen in hypolimnion needed to support lake trout 2. Water recreation of all types including swimming 3. Aesthetics
Stream trout lakes	1. Protection of sensitive aquatic community. Specifically, maintenance of adequate dissolved oxygen in metalimnion needed to support stream trout 2. Water recreation of all types including swimming 3. Aesthetics
Lakes and reservoirs > 15 feet deep	1. Water recreation of all types including swimming, at least part of the summer season 2. Maintenance of the desired game fishery 3. Aesthetics
Shallow lakes and reservoirs < 15 feet deep	1. Protection of aquatic community. Specifically the maintenance of a diverse community of emergent and submerged aquatic plants, and wildlife 2. Water recreation of all types including primary body contact where usable 3. Aesthetics

e. Candidate Variables

In the 1988 guidance criteria, MPCA selected TP as the only variable for which to develop nutrient criteria. For the nutrient criteria currently being developed, MPCA is again proposing the use of TP as a candidate criterion. This decision was based in part because most of the lakes in Minnesota are P-limited. Additionally, TP concentrations are closely linked with Chl-*a* concentrations, which serve as a surrogate for phytoplankton biomass. Furthermore, TP is considered an appropriate variable to use in identifying cultural eutrophication because sediment-diatom data can be linked to TP levels for comparing modern conditions with pre-European conditions.

In addition to choosing TP concentrations as a candidate criterion, MPCA is proposing the use of two response variables: Chl-*a* concentrations and Secchi depth. The proposal to use Chl-*a* levels and SD is in part due to the U.S. EPA's technical guidance (U.S. EPA 2000a). Public input concerning Minnesota's 303(d) list (impaired waters list reported by states and authorized tribes to U.S. EPA) has also led MPCA to consider the use of response variables. Furthermore, MPCA chose Chl-*a* concentrations and SD because of the close relationships among TP levels, Chl-*a* values, and SD ($r^2 > 0.70$) as well as the associations of Chl-*a* concentrations and SD with nuisance algal blooms and hypolimnion oxygen demand. Additionally, Chl-*a* levels and SD have been used to accompany user-perception responses. A review of the scientific literature (Heiskary and Wilson 2005) also indicates these are appropriate variables upon which to build nutrient criteria.

f. Water Quality Patterns

Because MPCA is proposing ecoregion-nutrient criteria, the agency stresses the importance of knowing the ranges of TP levels, Chl-*a* concentrations, and SD data, both within and among ecoregions. To determine these ranges, MPCA analyzed data from Minnesota's reference database and from MPCA's and U.S. EPA's water quality assessment databases. MPCA determined the 75th percentile of TP concentrations, Chl-*a* levels, and SD for reference lakes within each ecoregion and for special lake classes within the respective ecoregions. Likewise, MPCA calculated typical conditions for the assessment databases by considering the 25th and 75th percentiles for each ecoregion and lake class (Heiskary and Wilson 2005).

g. Candidate Threshold Conditions

A threshold can be defined as the concentration at which an effect, such as eutrophication or biological impairment, begins to occur. U.S. EPA's technical guidance manual (2000a) suggests that states and authorized tribes establish reference conditions, examine the historical record, and employ models if necessary to determine candidate threshold conditions. MPCA used these approaches to propose candidate threshold values for TP levels, Chl-*a* concentrations, and SD for each ecoregion and lake class. Below is a brief description of a few of the numerous studies undertaken by MPCA. Additional approaches and more detailed information can be found in Heiskary and Wilson (2005).

(1) Carlson's Trophic State Index (TSI)

Using Carlson's TSI (Carlson 1977), MPCA estimated the trophic status of the lakes in the reference database. This TSI relies on the interrelatedness of the SD measurements, TP concentrations, and Chl-*a* levels to estimate the trophic status of lakes from one or more of the variables. The TSI calculations indicated the following trophic status for the reference lakes in the four ecoregions:

- NLF ecoregion -- mesotrophic to mildly eutrophic;
- CHF ecoregion -- eutrophic;
- WCP ecoregion -- eutrophic to hypereutrophic;
- NGP ecoregion -- hypereutrophic (Heiskary and Wilson 2005).

(2) Historical Reconstruction of In-lake Phosphorus

To estimate the historical conditions of Minnesota's lakes, sediment cores from some Minnesota lakes were collected, sectioned, and dated. Diatoms within the cores were identified and

enumerated for the years corresponding to 1750, 1800, 1970, and 1993. Using water quality data collected in 1993 and the diatom data from that same year, correlation models were developed. These models were used to predict pre-European TP levels and other water quality parameters (Heiskary and Wilson 2005).

The data from the diatom-water quality studies indicated that lakes in the NLF ecoregion had lower TP concentrations compared to the other ecoregions. Furthermore, based on this method, the modern-day water quality of NLF lakes appeared to be similar to that predicted for pre-European settlement. In contrast, the shallow lakes in the CHF, WCP, and NGP ecoregions indicated significantly higher TP levels in modern times compared to earlier times. The five deep lakes in the WCP ecoregion that were sampled indicated the highest modern day phosphorus levels but suggested little difference from conditions found during pre-European settlement (Heiskary and Wilson 2005).

(3) User Perception

The utilization of user-perception information involved the use of observer-perception surveys and water quality data, specifically SD and/or Chl-*a* levels. Thresholds were determined based on the water quality level (*e.g.*, Secchi depth) associated with the occurrence (frequency) of perceived impaired conditions. Based on the user-perception assessments, MPCA classified each lake as supporting, partially supporting, or not supporting the swimming and aesthetic uses. For example, lakes with perceived impaired swimming conditions less than 10 percent of the time and high algal levels less than 10 percent of the time were considered to be "supporting" the swimming and aesthetic uses. MPCA also related the nuisance frequency data to TSI values to characterize the lake trophic status. From their user-perception analyses, MPCA suggested a minimal Secchi depth range of 1.0 – 1.2 meters as a threshold to indicate non-support of the swimming use.

(4) Aquatic Life Requirements

Water temperatures between 8 – 15^{o}C and dissolved oxygen concentrations above 5 mg/L provide suitable conditions to support populations of lake trout (*Salvelinus namaycush*). Accordingly, MPCA used temperature and DO profiles obtained during the late summer (when temperatures and DO levels are most limiting to lake trout) to denote suitable habitats within 15 of Minnesota's lake trout lakes. Based on this study, MPCA found the suitable habitat area for lake trout to be relatively large in some lakes and small in others. A correlation of the TP and Chl-*a* data for the lakes with large areas of suitable habitat indicated that summer-mean TP concentrations are < 15 µg/L (usually 8 – 10 µg/L) and summer-mean Chl-*a* values are about 3 µg/L. The lakes in the study that offered a small area of suitable habitat, however, had similar TP and Chl-*a* values. Thus, the analysis does not provide specific TP or Chl-*a* threshold values, but it suggests that summer average TP values need to be below 15 µg/L. MPCA noted that this proposed TP threshold is above the oligotrophic/mesotrophic boundary (TP = 10 µg/L) often cited (Nurnberg 1996). It is also above the TP level (TP = 12 µg/L) that corresponds to a TSI (40) where lakes with lake trout populations declined to below 5 percent (in Heiskary and Wilson 2005: Schupp, unpublished data).

h. Proposed Nutrient Criteria

MPCA is proposing that summer threshold values for TP, Chl-*a*, and SD (based on the average for the growing season) be used as criteria. In order for the eutrophication standard to be exceeded, both the causal variable (TP) and one of the response variables (either Chl-*a* or Secchi depth) would need to be exceeded. MPCA is also recommending that site-specific criteria be developed for reservoirs, water supply lakes, and other special circumstances. For example, lake-specific criteria could be developed for lakes not meeting the criteria because of natural causes (based on lake-specific monitoring data and other relevant information). An antidegradation rule is also proposed to protect the water quality of lakes that meet the criteria from being degraded to a lower level of quality (MPCA 2007).

MPCA's proposed threshold values for TP, Chl-*a*, and SD were chosen based on a weight of evidence and information derived from the various analyses described in Heiskary and Wilson (2005). The TP thresholds were established first. Research used in developing TP guidance criteria for Minnesota's lakes (Heiskary and Wilson 1988) was prominently considered when establishing the currently proposed TP thresholds. The Chl-*a* and SD thresholds were derived from their relationship with TP and each other, user-perception information, and various regression equations. MPCA considered an abundance of information, including, but not limited to, the following (Heiskary and Wilson 2005):

- 75^{th} percentile of TP data in the reference lake population;
- 25^{th} and 50^{th} percentiles of TP data in MPCA's assessed lake population;
- 25^{th} and 50^{th} percentiles of TP data in U.S. EPA's aggregated ecoregions that contain Minnesota's lakes;
- 75^{th} percentile of TP data predicted for lakes prior to European settlement;
- 75^{th} percentile of Chl-*a* and SD data in the reference lake population;
- 25^{th} and 50^{th} percentiles of Chl-*a* and SD data in MPCA's assessed lake population;
- 25^{th} and 50^{th} percentiles of Chl-*a* and SD data in U.S. EPA's aggregated ecoregions that contain Minnesota's lakes;
- TP, Chl-*a*, and SD associations from Carlson's TSI;
- User perceptions compared to SD and Chl-*a* data;
- Most sensitive sub-uses;
- For coldwater fisheries: Interrelationships among TP, Chl-*a*, SD, and hypolimnetic; oxygen depletion based on the literature and data from assessed lake trout lakes;
- For coolwater fisheries: Conditions required to maintain stream trout fisheries, metalimnion oxygen concentrations;
- For warmwater fisheries: Relationship among lake trophic state (expressed as TSI) and community shifts in species;
- For shallow lakes: TP, Chl-*a*, and SD measurements compared to rooted macrophytes;
- Relevant scientific literature.

The proposed thresholds for each ecoregion and lake class are described below and shown in Table III-4:

Northern Lakes and Forests (NLF) ecoregion

Some lakes in the NLF ecoregion support natural populations of lake trout; others are managed to support stream trout; and some are not able to support trout fisheries. Thus, the

most sensitive sub-uses for this ecoregion were identified as coldwater fisheries for lake trout lakes, coolwater fisheries for stream trout lakes, and primary contact for the remaining lakes in the ecoregion. No separate lake class was established for shallow lakes in the NLF ecoregion because the differences among the trophic status (based on TP concentrations) for deep and shallow lakes in this ecoregion were not significant.

North Central Hardwood Forest (CHF) ecoregion

The CHF ecoregion has no lakes that support natural populations of lake trout and only a few lakes that are managed for stream trout. The most sensitive sub-uses for CHF therefore include support of coolwater fisheries for those lakes that are managed for stream trout fisheries and aquatic recreation (primary contact). A separate class was established in the CHF ecoregion for shallow lakes. MPCA states that its main goal for establishing nutrient criteria for shallow lakes is "to allow for a healthy and diverse population of macrophytes and to minimize the chance for a shift to algal-dominated conditions" (Heiskary and Wilson 2005, p. 118).

Western Corn Belt Plains (WCP) and Northern Glaciated Plains (NGP) ecoregions

The WCB and NGP ecoregions were considered as one region for the purpose of proposing eutrophication criteria because these two ecoregions share similar characteristics in watershed land use, lake morphometry, water quality, aquatic ecology, and user perception. Neither lake trout lakes nor stream trout lakes are located in these two ecoregions so no special lake class was needed to protect these uses. Therefore, the most sensitive sub-use for the WCB and NGP ecoregions is aquatic recreation. The WCP ecoregion has several deep lakes for which criteria are being proposed; however, most of the lakes in these two ecoregions are shallow. Because the reference lakes for these two ecoregions indicate eutrophic or hypereutrophic conditions, MPCA is proposing a "partial support" of the aquatic recreational use. The goal for meeting this partial support is to reduce the frequency and severity of nuisance algal blooms (Heiskary and Wilson 1989, Heiskary and Wilson 2005).

In addition to proposing criteria, MPCA has also described its monitoring strategy for assessment compliance. Monitoring for compliance will occur during the growing season (about June through September). Four to eight monitoring events are to occur during this period for each monitored lake, with the resulting data being averaged over the entire growing season. Standard physical and chemical monitoring data will be collected, including TP concentrations, Chl-*a* levels, and Secchi depth. Oxygen and temperature profiles will be taken to assess the stratification status and to provide information about the amount of oxygen in the metalimnion and hypolimnion. For natural lakes, samples will be taken at one or more mid-lake sites. Reservoirs sampling will be site specific with most samples likely collected near the dam. Monitoring data obtained by MPCA will be supplemented with SD measurements and user-perception surveys collected by volunteers in the state's Citizen Lake Monitoring Program. For 303(d) listing purposes, at least 12 paired data points (either: [1] TP and Chl-*a* or [2] TP and SD) are required (Heiskary and Wilson 2005).

Table III-4. Proposed eutrophication criteria by ecoregion and lake type. (Source: Heiskary and Wilson 2005).

Ecoregion	TP	Chl-a	Secchi
	ppb	ppb	meters
NLF – Lake trout (Class 2A)	< 12	< 3	> 4.8
NLF – Stream trout (Class 2A)	< 20	< 6	> 2.5
NLF – Aquatic Rec. Use (Class 2B)	< 30	< 9	> 2.0
CHF – Stream trout (Class 2a)	< 20	< 6	> 2.5
CHF – Aquatic Rec. Use (Class 2b)	< 40	< 14	> 1.4
CHF – Aquatic Rec. Use (Class 2b) Shallow lakes	< 60	< 20	> 1.0
WCP & NGP – Aquatic Rec. Use (Class 2B)	< 65	< 22	> 0.9
WCP & NGP – Aquatic Rec. Use (Class 2b) Shallow lakes	< 90	< 30	> 0.7

i. Adoption of Water quality Standards

MPCA will adopt eutrophication standards following the procedures set forth in the rules of the Office of Administrative Hearings, Minnesota Rules, parts 1400.2200 to 1400.2240 and the Administrative Procedure Act, Minnesota Statutes, sections 14.131 to 14.20. The proposed nutrient criteria were approved by the governor of Minnesota in the summer of 2007. A series of public hearings has been set for late August and September 2007. More information, including the text of the proposed amendments and *Statement of Need and Reasonableness* (SONAR) is at http://www.pca.state.mn.us/water/standards/rulechange.html. The rulemaking process is expected to be complete by the end of 2007.

3. Virginia's Approach

The Virginia Department of Environmental Quality (VDEQ) worked with various researchers and stakeholders to propose nutrient criteria for lakes and reservoirs in Virginia. The researchers reviewed the scientific literature, conducted analyses of relevant databases, and made recommendations to VDEQ for establishing nutrient criteria. VDEQ used the recommendations of these researchers to initiate the state rulemaking process. One public meeting, four ad-hoc advisory committee meetings, and one public hearing were held. From this combined input, VDEQ developed amendments to the Virginia Water Quality Standards regulation (9 VAC 25-260). On June 1, 2006, the Virginia State Water Control Board adopted amendments to the Virginia Water Quality Standards regulations to become effective after approved by U.S. EPA. Before submission to U.S. EPA, the amendments were filed with the Virginia Department of Planning and Budget, underwent executive review, were filed with the *Virginia Register of Regulations*, and certified from the Office of the Attorney General stating that the amendments were duly adopted according to state law. Following this process, VDEQ submitted the

amendments to U.S. EPA on January 3, 2007. Approval from U.S. EPA was granted in July 2007. The proposed criteria are currently under review for public comment (August 2007).

The approach used to propose nutrient criteria in Virginia is described below.

a. Designated Uses to Protect

As part of the criteria development process, VDEQ sought the advice of an interdisciplinary research team known as the Academic Advisory Committee (AAC). The AAC adopted the position that the primary goal underlying the development of nutrient criteria is the support of *designated uses* of water. This approach meets the intent of the Clean Water Act and U.S. EPA requirements. In Virginia, all state waters have the following designated uses: "recreational uses, *e.g.*, swimming and boating; the propagation and growth of a balanced, indigenous population of aquatic life, including game fish, which might reasonably be expected to inhabit them; wildlife; and the production of edible and marketable natural resources, *e.g.*, fish and shellfish." (9 VAC 25-260). There are also special criteria (*e.g.*, iron and manganese concentrations) for public water supply reservoirs to maintain acceptable taste, odor, and aesthetic quality at the drinking water intake (9 VAC 25-260).

The AAC chose the support of recreational fisheries as the primary use to be protected. The population status of fish species sought by recreational anglers was considered to be an appropriate indicator for supporting both recreational and aquatic life support uses because such fish species are usually the top predators within the system and thus depend on an adequate supply of lower level aquatic organisms to survive. The AAC decided that developing criteria to protect the swimming use would be extremely subjective because the criteria would need to be based on user perception, which tends to depend on the quality of the water to which the user is accustomed (see Section II-E). Furthermore, water supply managers commented that they could manage algal levels higher than those identified to protect recreational fisheries. Therefore, the nutrient criteria proposed by the AAC to protect recreational fisheries is believed to also protect the water supply designate use.

b. Lakes/Reservoirs Classification

The two natural lakes in Virginia, Mountain Lake in southwest Virginia and Lake Drummond within the Great Dismal Swamp of southeast Virginia, were separated for criteria development from the reservoirs. Lake-specific criteria were developed for the two natural lakes.

The AAC classified the reservoirs monitored by VDEQ according to the type of recreational fishery it could support: coldwater, coolwater, or warmwater fisheries. A special "fertilized fishery" classification was given to reservoirs that are fertilized for increased fish production. The coldwater fisheries of Virginia's public reservoirs include mostly small (<100 acres) systems managed for trout. Some reservoirs, generally large reservoirs (> 500 acres), are managed for a combination of coolwater (*e.g.*, striped bass, walleye) and warmwater (sunfish, largemouth bass, catfish) species (but were classified as coolwater fisheries). Reservoirs managed solely for warmwater fisheries range from large systems (primarily in eastern Virginia) to ponds (and thus not considered in the rulemaking process). The Virginia Department of Game and Inland Fisheries (VDGIF) owns several small reservoirs that are managed (*e.g.*, fertilized) to support sportfishing.

Ecoregional criteria were developed for 116 constructed reservoirs. The ecoregions used in this process correlate with the aggregate nutrient ecoregions delineated by U.S. EPA in its nutrient criteria technical guidance (U.S. EPA 2000a). The reservoirs in Virginia belong to U.S. EPA's aggregate nutrient ecoregions 9, 11, and 14.

c. Candidate Variables

Phytoplankton are the dominant primary producers in Virginia's natural lakes and in almost all of the constructed reservoirs. Phytoplankton are also the direct cause of most nutrient-related designated use impairments. Because chlorophyll-*a* concentrations are an easily monitored proxy for algal biomass, the AAC recommended that concentrations of chlorophyll-*a* should be the basis for establishing nutrient-related criteria. Furthermore, correlations between chlorophyll-*a* concentrations and recreational fisheries status have been documented (*e.g.*, Schupp and Wilson 1993; see Section II-D). Chlorophyll concentrations can also indicate taste, odor, and/or toxicity effects that arise from algal blooms in reservoirs used as drinking water sources and reductions in water column transparency that diminish swimming and other recreational uses during algal blooms. Therefore, the recommendation to use chlorophyll-*a* levels was based on a review of the literature and the collective judgment of the AAC.

When algicides are applied to reservoirs to control taste and odor issues associated with certain algae however, chlorophyll-*a* concentration cannot accurately indicate the status of eutrophication. Therefore, the AAC also recommended that total phosphorus (TP) concentrations be used as candidate nutrient criteria for reservoirs when algicide are used. Studies of natural lakes have shown close associations between TP levels and algal biomass (*e.g.*, Dillon and Rigler 1974; Rast *et al*. 1983). The AAC did not recommend nitrogen criteria because some nuisance, bloom-forming cyanobacteria are nitrogen fixers. Reductions of nitrogen without reductions in phosphorous could increase the likelihood of stimulating blooms of N-fixing primary producers. Furthermore, Secchi depth was not considered an appropriate candidate criterion for determining nutrient over-enrichment in reservoirs because water transparency is often affected by inorganic turbidity in impoundments (*e.g.*, Jones and Knowlton 1993, Knowlton and Jones 1993).

Empiric relationships between fisheries productivity (as measured by fish harvest, production, or biomass) and both primary production and phosphorus concentration have been developed and published for regional and global sets of lakes. Correlations between primary production and fisheries productivity are highly positive, the former explaining (r^2) 67 – 84% of the latter (Melack 1976, Oglesby 1977, Liang *et al*. 1981, Jones and Hoyer 1982, Downing *et al*. 1990). Correlations between total phosphorus (TP) concentration and fisheries productivity are similarly strong (51 – 84%) (Hanson and Leggett 1982, Jones and Hoyer 1982, Downing *et al*. 1990, Ney *et al*. 1990).

d. Proposed Nutrient Criteria

(1) Natural Lakes

For the two natural lakes, Mountain Lake and Lake Drummond, the VDEQ worked directly with the researchers most knowledgeable about these lakes. Using the literature, data from the lakes,

and best professional judgment, lake-specific criteria were developed. Proposed nutrient criteria levels for Mountain Lake include: chlorophyll-*a* ≤ 6 µg/L at a depth of 6 meters and orthophosphate-P ≤ 8 µg/L at a depth of one meter or less. The proposed criteria for Lake Drummond was set at 35 µg/L for chlorophyll-*a* and 40 µg/L for total phosphorus at a depth of one meter or less (9 VAC 25-260-310).

(2) Reservoirs

Virginia has 116 constructed reservoirs for which VDEQ proposed nutrient criteria. These reservoirs include those for which VDEQ has previously monitored, currently is monitoring, or will be monitoring in the upcoming assessment cycle. For these constructed water bodies, VDEQ worked with the AAC in developing an approach that is acceptable to stakeholders, the State Water Control Board and U.S. EPA. The AAC reviewed the published literature for sportfish species found in Virginia's reservoirs (see Section II-D) and used these values as supplementary data. The criteria were proposed using an assessment of the fishery status and water quality information from reservoirs that support the best fisheries in Virginia.

(i.) Literature Values[4]

-- *Coldwater Fisheries:* The goal for Virginia's reservoirs that support coldwater fisheries is to provide production levels that promote the growth of trout populations and protects an oxygenated hypolimnion during thermal stratification (protects trout habitat). The literature by Schupp and Wilson (1993), Elliott *et al*. (1996), and Johnston *et al*. (1999) indicates that Chl-*a* levels at or below 6 µg/L and TP levels at or below 10 µg/L would be adequate to sustain trout habitat and promote trout growth.

-- *Coolwater Fisheries:* Virginia's coolwater sportfish species prefer water temperatures in the range of 19°C – 28°C (Coutant 1985, Hokanson 1990, Kilpatrick 2003) and include striped bass, hybrid striped bass (white bass x striped bass), and walleye. These species tend to be limited to the metalimnion/hypolimnion of the downlake region near the dam in Virginia reservoirs (Ney 1988, Kilpatrick 2003). These species grow poorly under oligotrophic conditions, preferring mesotrophic waters that support a large supply of forage fishes (*e.g*., gizzard shad, threadfin shad) (Ney 1988, Schupp and Wilson 1993, Anderson 2001, Bremigan and Stein 2001, and Maceina 2001). Based on the reviewed literature, coolwater fisheries can be expected to prosper in systems where Chl-*a* ≤ 15 µg/L and TP >10 µg/L.

-- *Warmwater Fisheries:* Warmwater sportfish include the sunfish family (Centrarchidae) and catfishes. Because catfish have higher temperature and lower dissolved oxygen (DO) tolerances than centrarchids, the AAC focused on conditions that support sunfishes (bluegill, redear, redbreast, and pumpkinseed), black and white crappie, smallmouth bass, and largemouth bass. Centrarchids are littoral and epilimnetic fishes that do not require an oxygenated hypolimnion as summer habitat. Thus, centrarchid populations tend to be food-limited rather than habitat-limited. Higher levels of nutrients tend to correlate with more biomass of centrarchids. In fact, small lakes that support centrarchid fisheries are often fertilized at least annually. Based on the reviewed literature (Schupp and Wilson 1993, Bachmann *et al*. 1996, Maceina *et al*. 1996, Maceina 2001), warmwater fisheries are expected to thrive where Chl-*a* is 20 – 40 µg/L and TP ≤ 50 µg/L.

[4] This section was written by J.J. Ney. Modifications have been made from the original source, Zipper *et al.* (2005).

(ii.) Water quality and Fishery-Status Data
As part of VDEQ's routine lake monitoring, water samples are collected from one meter or less within the lacustrine portion of each sampled reservoir between April 1 and October 31 (one sample per month). Following a procedure that is analogous to U.S. EPA's approach, the April to October monitoring period was divided into four components for each reservoir. A 90th percentile for Chl-*a* and a median (50th percentile) value for TP were then calculated for each of the four periods. The median of these respective values was then used to obtain a 90th percentile value for Chl-*a* and a median concentration for TP for each monitored reservoir.

The 90th percentile for Chl-*a* was chosen based on input from stakeholders and the VDEQ ad-hoc advisory committee. This percentile was used in an attempt to reflect the maximum chlorophyll-*a* concentrations that occur during conditions favorable to algal growth. The "maximum" chlorophyll-*a* concentration was considered to be a more appropriate basis for criteria development than the median chlorophyll-*a* values because the maximum algal biomass levels are most likely to cause extreme DO depletions. Consequently, extreme DO depletions will have the greatest influence on fish populations.

For phosphorus levels, the typical reservoir condition was desired. Therefore, a median TP concentration was used.

Concurrent with the analysis of the VDEQ monitoring data, the recreational fishery status was assessed for each reservoir. Biologists from the VDGIF rated the recreational fishery status on a scale of 1 (poor) to 5 (excellent): 1 = poor (anglers would be advised to avoid such reservoirs); 2 = fair (anglers would be advised to not expect much in the way of fishing success); 3 = average (the reservoir supports adequate fishery); 4 = good (the reservoir is recommended for fishing); and 5 = excellent (the reservoir is highly recommended for fishing).

Graphs were developed for reservoirs within a given ecoregion from which both a fishery status had been obtained and water quality values were known. First, for each reservoir, the 90th percentile Chl-*a* value (x-axis) was plotted against its respective fishery status (y-axis), and second, the median TP value (x-axis) was graphed in comparison to the fishery status (y-axis). These graphs were then used to select optimum chlorophyll-*a* and TP values that will sustain good-to-excellent recreational fisheries (fishery status 4 and 5) for each fishery type (*e.g.*, coolwater, warmwater) within the three different aggregate nutrient ecoregions in Virginia (ecoregion 9, 11, and 14).

(iii.) Use of Best Professional Judgment
The AAC used the scientific literature concerning algal and nutrient influences on fisheries in association with the results of the water quality-fishery status analysis to propose nutrient criteria for reservoirs in Virginia. The final recommended criteria to support viable recreational fisheries are summarized in Table III-5.

Within fisheries, individual species respond differently to particular levels of primary production. For example, although black crappie and white crappie are both warmwater fish, black crappie populations thrive at chlorophyll-*a* levels of ~20 µg/L and TP ~60 µg/L whereas white crappie do best under hypereutrophic conditions (chlorophyll-*a* ~60 µg/L; TP ~100 µg/L)

(Schupp and Wilson 1993). Acknowledging the uncertainties of setting numeric limits to support an entire fishery therefore, VDEQ wrote the proposed regulations so that exceedances of the criteria would initiate a fishery assessment by the Virginia Department of Game and Inland Fisheries. The purpose of the VDGIF assessment is to determine whether or not the recreational fishery for the reservoir in question is being supported. Furthermore, the regulations call for reservoir-specific criteria to be developed if needed.

Table III-5. Final candidate criteria to accommodate fishery recreation and protect aquatic life.

Fishery Type	Warm-water	Cool-water	Cold-water (trout)	Managed / Fertilized	Warm-water	Cool-water	Cold-water (trout)	Managed / Fertilized
Eco-region	- - - - - - - - Chl-*a* (µg/L)[a] - - - - - - - -				- - - - - - - - TP (µg/L)[b] - - - - - - - -			
11	35	25	10		40	20	10	
9	35	25		60	40	30		40
14	60	25			40	20		

[a] Chl-*a* are 90th percentile values representative of the April – October period.
[b] TP are the median values representative of the April – October period.

e. Adoption of Water quality Standards

Using the AAC recommendations and the input from stakeholders and the ad-hoc advisory committee, the VDEQ developed amendments to the Virginia Water Quality Standards regulation (9 VAC 25-260) by adding new numerical and narrative criteria to protect the designated uses of lakes and reservoirs from nutrient impacts. In July 2007, the U.S. EPA approved the proposed criteria. The amendments are currently (August 2007) available for public comment, and the rulemaking process is expected to be complete in fall 2007.

The proposed nutrient criteria amendments include:

- Numeric chlorophyll-*a* and phosphorus criteria for Virginia's two natural lakes and 116 listed reservoirs (phosphorus applies only in reservoirs treated with algicides);
- A procedure for confirmation of use impairments in reservoirs when nutrient criteria are exceeded (based on the status of the fishery);
- A provision for the development of site-specific criteria for reservoirs where the numeric criteria are exceeded but the designated uses of the water body are being attained (waters are considered impaired until the site-specific criteria are adopted and become effective);
- An allowance for site-specific modifications to the criteria if the specified nutrient criteria do not protect downstream waters.

4. Arizona's Approach

The Arizona Department of Environmental Quality (ADEQ) worked with a contractor to develop a "translator" approach to interpret Arizona's narrative nutrient criteria. Translators are calculations used to better relate a measurable numeric value to a narrative criteria. A trophic index is an example of a statistical translator. It can be used to relate concentrations of nitrogen

and phosphorus to direct indicators of eutrophication, such as chlorophyll-*a* concentrations. The use of translators is supported by U.S. EPA in *Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs* (2000a).

ADEQ is proposing a "narrative nutrient implementation matrix" to explain (or translate) whether or not its current narrative nutrient criteria are being met. Arizona's current narrative nutrient criteria states:

> *A surface water shall be free from pollutants in amounts or combination that…cause the growth of algae or aquatic plants that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses…*(Arizona Administrative Code R18-11-108(A)(7)).

The contractor developed a matrix of numeric targets for lake and reservoir water quality parameters that are expected to support various designated uses. A weight-of-evidence protocol will be used to interpret the narrative nutrient criteria by systematically comparing monitoring data with the targets. The numeric targets were selected based on a review of the scientific literature, statistical analyses of water quality data from Arizona's lakes and reservoirs, and a trophic state index developed specifically for Arizona's lakes and reservoirs (ADEQ 2005). This proposed approach has the advantage of linking water quality targets with the attainment of specific designated uses (Malcolm Pirnie 2005). Below is an overview of the approach.

a. Literature Review

The contractor first conducted a review of the scientific and lake management literature, specifically focusing on whether or not certain levels of nutrient-related parameters (*e.g.*, Chl-*a*, TP, *etc*.) support various designated uses (*e.g.*, recreation, fisheries and aquatic life support, and public water supply). The literature review also included studies that identify numeric values that reflect use impairment. This work is summarized in Table III-6 (Malcolm Pirnie 2005).

The literature review included research specific to Arizona's lakes and reservoirs as well as studies from other states, the federal government, and outside the U.S. For example, Arizona used the fisheries literature review developed by Virginia to link the fishery status to Chl-*a* levels (see Section II-D and this section, Virginia's Approach). As another example, recommendations made by the World Health Organization (WHO) were included to protect human health from excessive levels of cyanobacteria. Specifically the WHO recommends cyanobacterial levels ≤ 20,000 cells/mL to protect against irritative or allergenic health effects (Chorus and Bartuam 1999 in Malcolm Pirnie 2005). Furthermore, an analysis of Arizona's lakes and reservoirs concluded that cyanobacterial levels exceeding 20,000 cells/mL were more likely when Chl-*a* levels exceeded 10 – 15 µg/L and when TN exceeded 1.5 – 1.7 mg/L (Malcolm Pirnie 2005).

b. Designated Uses to Protect

ADEQ considered the following designated uses as likely to be impacted by excessive nutrient concentrations: domestic water source (DWS), aquatic life and wildlife (A&W), and recreation. For the narrative criteria translation process, the recreation use included full-body contact (FBC) and partial-body contact (PBC) but did not include fishing. Protection of recreational fisheries was included within the aquatic life and wildlife use and was subdivided into protecting warmwater fisheries and coldwater fisheries (ADEQ 2005).

Table III-6. Targets from the Scientific and Lake Management Literature (Source Malcolm Pirnie 2005. Reprinted with permission).

Beneficial Use	Parameter			Notes
	Tot. Phos. (µg/L)	Chl-*a* (µg/L)	Sec Dep. (m)	
Recreation				
Recreational Waters and Aesthetics		10 50 5,000		Mild/ low probability of health effects Moderate probability of short-term health effects High risk of long-term health effects (Pilotto et al., 1997)
		0-10 10-20 20-30 >30		No problems Scums Nuisance Severe nuisance (Walmsley, 1984)—South African Reservoir
		14 30 32	1.2 0.8 0.7	"Excellent to good" "Good to Acceptable" "Acceptable to Marginal" (Burden et al, 1985)—Louisiana
		0-25 25-100 100-200	>1 0.4-1 <0.4	Clear, no blooms Moderate blooms Dense colonies and scums (Barica, 1975)—Canadian prairie ponds
		<1 1-5 5-10 10-15 15-30 >30	>6 3-6 2-3 1.5-2 1-1.5 <1	"Excellent" "Very Good" "Good" "Fair" "Poor" "Very Poor" (Lillie and Mason, 1983)—Wisconsin
		6-7 9-10 12-15 15-20		Algae begins to be noticeable. Definite observable levels of algae. Algae levels moderate. Swimming uses begin to be impaired. Algae level high. Contact recreation impaired.

Beneficial Use	Parameter			Notes
	Tot. Phos. (µg/L)	Chl-*a* (µg/L)	Sec Dep. (m)	
		20-25 30-80		No swimming due to concerns for human health Severe algal scums. Recreational/aesthetics severely impaired. Kansas Lakes (Carney, 1998)
	<10	2	2-5	Lake will be clear but will not support a highly productive fishery. (Dillon et al 1975)
	30-40			Full body contact supported (Minnesota) NALMS 1992.
	90			Partial body contact (Minnesota) NALMS 1992.
	<30			Northern Lakes and Forests Ecoregion, Minnesota (Heiskary and Wilson, 1989).
	<40			Northern Central Hardwood Forests, Western Corn Belt Plains, and Northern Glaciated Plains Ecoregions, Minnesota (Heiskary and Wilson, 1989).
	<90			Partial support of primary contact recreation, Western Corn Belt Plains and Northern Glaciated Plains Ecoregions, Minnesota (Heiskary and Wilson, 1989).
Recreational Waters	<25		0.2-2.2	Lake Champlain. (Heiskary et al, 1989)
	25-29			Algal greenness present, use slightly impaired (Lake Champlain). (Smelter et al, 1990).
Swimming and Aesthetic Uses	40	>30		Swimming considered impaired in northern locales (Minnesota, Wisconsin) (Smeltzer et al, 1990)
	>25			High algal level, enjoyment substantially reduced (Lake Champlain). (Smeltzer et al, 1990).
			1.5	Swimmers prefer blue waters to yellow. (Smith et al, 1995).
Swimming and Aesthetic Uses	52	40-60	0.3-1.35	Nuisance to severe nuisance, no swimming. (Smeltzer et al, 1990).
	<10			British Columbia Standards (EPA, 2000).
Fisheries				
Coldwater Fisheries	<24			Natural lakes (Oglesby, 1977)
	5-15			British Columbia Standards (EPA, 2000).
		10	1-2	Support of fisheries only, not recreation (Dillon et al, 1975).
	6	1		Peak abundance of Minnesota lake trout populations (Schupp and Wilson, 1993).
	<15			Full support of coldwater fishery, Northern Lakes and Forests Ecoregion (Minnesota). (Heiskary and Wilson, 1989)
		15		Trout waters (McGhee, 1983)—North Carolina
	<24			Natural lakes (Oglesby et al, 1977)

Table continues on next page.

Beneficial Use	Parameter			Notes
	Tot. Phos. (µg/L)	Chl-*a* (µg/L)	Sec Dep. (m)	
Coolwater Fisheries	15-25	7-10	>4	Chl *a* and secchi depth from Minnesota lakes in: Schupp and Wilson 1993
	>10			TP<10 show declines in fish health (Lake Mead). (Axler et al, 1987).
	24-48			Natural lakes (Oglesby et al, 1977)
		5-15		Supports Lake Erie walleye population (Anderson et. al. 2001)
Warmwater Fisheries	48-193	40-60	0.5	Fertilization to achieve Chl *a* concentrations for production of bass and sunfish (Maceina, 2001).
		40		Bachman et al. 2002 confirms trophy fish are more abundant in more eutrophic lakes.
		40		Non-trout waters (McGhee, 1983)—North Carolina
		25		Warmwater fisheries only (Dillon et al, 1975).
		60-70	0.5	Hyperutrophic status for managed ponds, no recreation. (Lee et al 1995)
	50-200			Eutrophic, limited body contact, productive warmwater fisheries. (Reckhow, et al, 1980).
	60	20		Black crappie fisheries peak (Schupp and Wilson, 1993).
	100	60		White crappie fisheries peak (Schupp and Wilson, 1993).
		10-15		These chl *a* levels not necessarily detrimental to black bass and crappie fisheries. (Maceina et al, 1996).
		20		Growth of crappie and largemouth bass increased up to this chl-a level (Maceina, 1996).
	>48			Natural lakes (Oglesby et al, 1977)
Domestic				
Potable Water/Drinking Water		30		Chl *a* values above 30 µg/l increase the risk of algal-related health problems, (Heath et al 1988).
	<10			Phosphorus criteria from British Columbia (EPA, 2000).
		9-10 15-20 20-80		Taste and odor problems become noticeable Water supply use impaired. Consumptive uses severely impaired. Kansas lakes (Carney, 1998)

c. Databases

The contractor obtained data pertinent to threshold development for approximately 70 lakes and reservoirs in Arizona. They used water quality data only for the growing season, defined as May to September for high elevation lakes/reservoirs (> 5,000 feet) and April to October for low elevation lakes (< 5,000 feet). Water quality data included (but were not limited to) water temperature, pH, DO, Chl-*a*, TP, TN, TKN, and ammonia. For some water bodies, the monitoring data spanned a 20-year period. The developed database also included information about the lake or reservoir, such as its location, source water, mean depth, size, shape, geology/soil of the watershed, and land use within the watershed (Malcolm Pirnie 2005).

d. Lakes/Reservoirs Classification

Using the data pertaining to the 70 lakes/reservoirs, the contractor conducted simple descriptive statistics. The analyses revealed that the lakes and reservoirs within the state differ from one another. Principle Components Analysis (PCA) was used to examine the structure of the relationships among the different variables and to determine which factors explained most of the variability and thus would likely be useful in classifying the water bodies. To group the lakes and reservoirs with similar characteristics, a Classification and Regressions Tree (CART) analysis was performed (ADEQ 2005, Malcolm Pirnie 2005).

Although some lakes/reservoirs may have attributes that would allow them to be categorized in more than one class, each lake or reservoir was assigned a primary classification. Most of the water bodies were categorized into one of five different classes: deep, moderately deep with igneous geology, moderately deep with sedimentary geology, shallow, or urban (ADEQ 2005, Malcolm Pirnie 2005):

Deep lakes (n = 19): These lakes and reservoirs have average depths of more than 5.5 meters (18 feet). This class includes all of Arizona's large water supply reservoirs. Compared

to most lakes and reservoirs in Arizona, this class tends to have low nutrient concentrations and low chlorophyll-*a* values.

Moderately-deep lakes with igneous geology (n = 23): Lakes and reservoirs of this class have average depths between 3 to 5.5 meters and are located in watersheds dominated by igneous rock. These lakes and reservoirs are managed primarily for fishing and recreation. Compared to moderately deep lakes and reservoirs in watersheds dominated by sedimentary rock, these waters are more turbid so have shallower Secchi depth readings.

Moderately-deep lakes with sedimentary geology (n = 8): Lakes and reservoirs of this class have average depths of 3 to 5.5 meters and are situated in watersheds dominated by sedimentary rock. This class is primarily managed for fishing and recreation.

Shallow lakes (n = 12): These lakes and reservoirs have average depths of less than 3 meters and a maximum depth of less than 4 meters. Because the lakes and reservoirs of this class may be dominated by macrophytes (instead of phytoplankton), they tend to have higher Secchi depth readings and low to moderate levels of Chl-*a* compared to many other lakes and reservoirs in Arizona.

Urban lakes (n = 7): These are specialty lakes in that they meet the definition of shallow lakes but are located within an urban setting. These lakes and reservoirs tend to have relatively high nutrient concentrations, particularly those that receive reclaimed water. These waters are not generally used for either water supply or full-body contact, but some are used for partial-body contact. Also, the aquatic life and wildlife use for the urban class is limited to protecting "put and take fisheries."

Four lakes and reservoirs in the study did not fall into any of the above categories so were classified as "other" (Malcolm Pirnie 2005). The "other" classification would cover, for example, the few ephemeral natural lakes with an average depth of less than one meter and the lakes/reservoirs that are effluent dependent. Arizona may need to develop site-specific narrative nutrient criteria for both of these groups (ADEQ 2005).

e. Candidate Variables

Because most nutrient-related use restrictions result from blooms of algae or extensive growths of aquatic plants, the contractor recommended response variables as the primary candidate variables. Selection of these variables was based on the assumption that excess growth of algae or aquatic plants indicates excessive amounts of available nutrients in the water. Nutrient concentrations from the analysis of grab samples were not considered the best candidate variables because factors other than nutrients (such as hydraulic residence time, light availability, grazers, *etc*.) affect primary production (Malcolm Pirnie 2005). Thus, ADEQ chose chlorophyll-*a* concentrations for phytoplankton dominated waters and percent plant cover for macrophyte dominated waters as the primary candidate variables (ADEQ 2005).

Secchi depth, another response variable, was also recommended for assessing the attainment of the designated uses. For Arizona's lakes and reservoirs, Secchi depth was found to be correlated with Chl-*a* ($r^2 = 0.34$). Likewise, nutrient concentrations were included as secondary candidate variables because data from Arizona's lakes and reservoirs revealed significant correlations with Chl-*a* and TP ($r^2 = 0.25$), TN ($r^2 = 0.25$), and TKN ($r^2 = 0.52$) (Malcolm Pirnie 2005).

Based on the WHO recommendations, cyanobacterial levels were proposed to indicate attainment of the drinking water supply use and recreation use. Dissolved oxygen and pH standards were added as supportive variables for lakes and reservoirs where Chl-*a* values, nutrient concentrations, Secchi depth, and cyanobacterial levels could not indicate fulfillment or impairment of the narrative nutrient criteria (ADEQ 2005, Malcolm Pirnie 2005).

f.) Proposed Nutrient Thresholds

Thresholds were identified for both causal variables (TP, TN, TKN) and response variables (Chl-*a*, Secchi depth, cyanobacteria, DO, and pH) (Table III-7) (ADEQ 2005, Malcolm Pirnie 2005). ADEQ recommends the use of a range of threshold values because impairments tend to occur gradually over time. Furthermore, individual lakes and reservoirs respond differently to the amount of nutrients present (ADEQ 2005).

Table III-7. Matrix for Implementation of the Narrative Nutrient Standard in Lakes and Reservoirs (Source: ADEQ 2005. Reprinted with permission.).

		Response Variables								
Designated Use	Lake Category	Chl-a (□g/L)	Secchi Depth (m)	Blue-Green Algae (per mL)	Blue-Green Algae (% of total count)	Tot. Phos. (mg/L)	Tot. Nit. (mg/L)	TKN (mg/L)	Dissolved Oxygen (mg/L)	pH (SU)
DWS	Any/All	10-20	0.5-1.5	20,000	NA	70-100	1.2-1.5	1.0-1.2	NA	5.0 – 9.0
Recreation										
FBC PBC	Deep	10-15	1.5-2.5	20,000	NA	70-90	1.2-1.4	1.0-1.1	NA	6.5 – 9.0
	Shallow	10-15	1.5-2.0		NA	70-90	1.2-1.4	1.0-1.1	NA	
	Igneous	20-30	0.5-1.0		NA	100-125	1.5-1.7	1.2-1.4	NA	
	Sedimentary	20-30	1.5-2.0		NA	100-125	1.5-1.7	1.2-1.4	NA	
	Urban	20-30	0.5-1.0		NA	100-125	1.5-1.7	1.2-1.4	NA	
Fisheries										
A&W/cold	Any/All	5-15	1.5-2.0	NA	<50	50-90	1.0-1.4	0.7-1.1	7 top m	6.5 – 9.0
A&W/warm	Any/All	25-40	0.8-1.0	NA		115-140	1.6-1.8	1.3-1.6	6 top m	
A&W/urban	Urban	30-50	0.7-1.0	NA		125-160	1.7-1.9	1.4-1.7		

NOTE: All lakes carry A&W as well as contact recreation (FBC or PBC) designated uses. Threshold ranges apply during "peak season" for lake productivity, including those for Domestic Water Source (DWS). Peak season for cold water lakes is May – September; peak season for warm water lakes is April – October. "NA" means not applicable

The contractor used 50 of the 70 lakes and reservoirs in the study to derive threshold ranges associated with attainment or impairment of uses in order to interpret (or translate) the narrative nutrient standard. The thresholds developed for Arizona's lakes and reservoirs were derived using the following information (ADEQ 2005, Malcolm Pirnie 2005):

- Arizona's existing numeric nutrient water quality criteria;
- U.S. EPA's proposed ecoregional numeric nutrient criteria;
- Effects-based targets adopted by other states (*e.g.*, Minnesota);
- Numeric targets derived from the scientific and lake management literature;
- Trophic-state indices developed for Arizona's lakes and reservoirs;
- Numeric ranges from watershed and in-lake loading models/methods.

Threshold values (numeric targets) were derived for each designated use and each lake class. Chl-*a* values were used as the primary threshold value. Secondary targets were established for Secchi depth, TP, TN, and TKN (ADEQ 2005). The contractor built an Arizona-specific trophic state index (TSI) that was based on the correlations of Chl-*a* levels with Secchi depth, TP, TN,

and TKN concentrations. Using this TSI, targets were set for Secchi depth and nutrients that would be expected to maintain specific levels of Chl-*a* in Arizona's lakes and reservoirs (Malcolm Pirnie 2005).

(1) Water Supply Use

To protect the water supply use, the contractor proposed Chl-*a* threshold values that are primarily based on information from the scientific and lake-management literature. Studies reported in the literature suggest that taste and odor problems can become noticeable at Chl-*a* levels as low as 10 µg/L, and that water supply uses can be impaired at 20 – 30 µg/L for Chl-*a* (in Malcolm Pirnie 2005: Heath *et al*. 1988, Carney 1998, U.S. EPA 2000a).

(2) Recreational Use

To protect the recreational use, the contractor suggested threshold values based on findings in the literature and the water quality characteristics of Arizona's different lake classes (deep, shallow, igneous, sedimentary, and urban). Although user-perception surveys were not incorporated in the target-setting process, the contractor suggests that users would object to noticeable degradation of water quality. Thus, the contractor proposed Chl-*a* targets that would meet the state's antidegradation policy. Based on monitoring data from Arizona's lakes and reservoirs, deep and shallow lakes/reservoirs were given lower targets for Chl-*a* than were moderately deep water bodies with igneous geology or sedimentary geology, and urban lakes/reservoirs. Secondly, because the recreational use includes full-body and partial-body contact, the contractor also proposed a cyanobacterial level that is expected to protect against allergenic health effects (Malcolm Pirnie 2005).

(3) Fisheries Use

The contractor relied on the scientific and lake/reservoir management literature to select possible Chl-*a* targets to protect the fisheries use. For example, the literature suggests that Chl-*a* values of 15 µg/L would likely impair coldwater fisheries (McGhee 1983 in Malcolm Pirnie 2005). Because the literature shows that warmwater fisheries can thrive at higher Chl-*a* levels, these waters were given higher targets, 25 – 40 µg/L. Likewise, because urban lakes and reservoirs need only to protect "put and take fisheries," the Chl-*a* targets for these waters, 30 – 50 µg/L, were even higher. Target ranges for Secchi depth were calculated from the Arizona TSI. The contractor also proposed a cyanobacterial count of less than 50 percent of the total algal count to prevent cyanobacterial dominance and a dissolved oxygen concentration for the top meter of water (Malcolm Pirnie 2005).

ADEQ (2005) intends to use the threshold values assigned by the contractor and a weight-of-evidence process to assess excessive algal or aquatic plant growth. For phytoplankton dominated lakes and reservoirs, chlorophyll-*a* concentrations are given the highest weight because they indicate the relative algal biomass. Cyanobacteria levels have the second highest weight because they can be linked to human health concerns. Secchi depth thresholds receive a lower weighting because Secchi depth values may be influenced by sediment and water color and thus must be evaluated along with suspended sediment data. For macrophyte dominated lakes and reservoirs, areal coverage of submerged aquatic vegetation is given the highest weight, and dissolved oxygen fluctuations in the photic zone are used as supplemental information (ADEQ 2005).

To determine use attainment, water samples collected during the growing season (warmwater: April – October; coldwater: May – September) are to be analyzed. As currently proposed, use attainment will be granted when the seasonal means fall below the lower threshold value (upper threshold for Secchi depth). Impairment will be assigned when there are at least two exceedances within a two-year to five-year assessment period (ADEQ 2005).

The recommended approaches for determining exceedances rely on the developed matrix (Table III-7) and the following (ADEQ 2005):

For phytoplankton dominated lakes and reservoirs:

- Mean Chl-*a* value exceeds upper threshold range
- Mean Chl-*a* value is within the threshold range, and the mean cyanobacterial level (count/mL or % of total count) is at or above the assigned threshold level
- Mean Chl-*a* value is within the threshold and additional evidence indicates nutrient-related impairments (*e.g.*, other parameters exceeded: TP, TN, TKN, Secchi depth, DO, and/or pH; additionally, fish kills associated with nutrient-related causes such as low DO levels or high ammonia concentrations)

For macrophytic dominated lakes and reservoirs (mean depth ≤ 4 m):

- Submerged aquatic vegetation exceeds 50% of the areal extent of the lake bottom and there is greater than 5 mg/L range in DO measurements taken from the photic zone in a 24-hour period.

Lakes and reservoirs where neither attainment nor impairment can be determined from the process above will undergo additional study to determine its listing status. Additional information — such as records of algal blooms, fish kills, poor fishery status, as well as taste and odor problems — will be used (ADEQ 2005).

g. Adoption of water quality standards

The proposed approach to determine compliance with the narrative nutrient criteria is currently (June 2007) in draft form. Arizona expects to finalize this implementation protocol by fall 2007 and begin using the standards in fall or winter 2007.

5. An Alternative Approach

An alternative method to developing nutrient criteria is being investigated as a dissertation project by Melissa Kenney at Duke University. In a paper published in the proceedings from the National Water Research Institute's First Annual Graduate Fellowship Research Conference, Kenney (2007) takes issue with the two most common approaches — use of ecoregion reference lakes and use of expert panels that rely on best professional judgment — for not statistically linking nutrient criteria to the designated use and for not separating scientific information from judgment decisions. Kenney (2007) proposes an alternative approach that (1) uses a statistical model to predict which nutrient-related parameters most likely indicate attainment of the designated use, and (2) predicts the criteria level that would maximize environmental protection while minimizing costs. This approach is currently (2007) being applied to lakes and reservoirs in North Carolina.

The first part of the proposed alternative method uses structural equation modeling (SEM) to identify the eutrophication-related variable(s) that are most predictive of designated use

attainment (Reckhow *et al*. 2005, Kenney 2007). Thus, SEM is used to determine which parameters to incorporate into the nutrient criteria development process. SEM uses both water quality data and expert elicitation data. The water quality data is used to describe the eutrophication processes. To link eutrophication to designated use attainment, expert elicitation was used to quantify designated use attainment. Expert elicitation is a method used to systematically obtain subjective judgments from experts. First, the modelers identify the designated uses that could potentially be impacted by nutrients, and then they interview knowledgeable state officials and/or university scientists familiar with the water body or water bodies about eutrophication and designated use attainment. The responses to the interviews are quantified on a categorical scale. Through SEM, the resulting elicitation-categorical data are linked to available water quality data to determine which parameters are most predictive of attainment of the designated use (Reckhow *et al*. 2005, Kenney 2007).

The second component of this alternative approach is referred to as nutrient criteria utility analysis. This analysis provides concrete recommendations to decision makers, based on their value judgments, to set a criterion level. The purpose is to help decision makers choose a criterion level that will find the optimal tradeoff level between maximizing environmental protection and minimizing costs. This analysis relies on the tradeoff decisions of multiple decision makers for meeting various environmental and societal objectives. In this application, utility analysis uses a modeling method called multiattribute utility analysis to determine the criterion level that maximizes the utility for one or a group of decision makers (Kenney 2007).

For the study of 132 North Carolina lakes and reservoirs, water quality data and expert elicitation data were obtained, and SEM was used to link the water quality data to eutrophication and designed uses. Separate models were developed to test two distinct designated uses (primary and secondary contact recreation). Models were also created to analyze ecoregion-specific data and pooled data from across the state. In total, more than 350 models were developed to evaluate the variables most predictive of the assigned designated uses. Two models consistently gave acceptable results. One of these models indicates that total phosphorus (TP) is the best predictor of use attainment whereas the other model shows that total inorganic nitrogen (TIN) is the best parameter on which to base nutrient criteria.

The researchers recommend using TP as the variable to assess use support for the lakes and reservoirs in North Carolina. They base this decision on the results of the modeling, the judgment of the experts that the lakes and reservoirs of North Carolina are phosphorus limited, and the fact that TP data are available for most monitored lakes and reservoirs in North Carolina. The nutrient criteria utility analysis component of the study is currently underway. Depending on the outcome of this research, this method may provide an alternative approach for states and tribes to use in developing nutrient criteria (Kenney 2007).

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Grant No. 06HQGR0189 Microtopography Effects on Vegetative and Biogeochemical Patterns in Created Wetlands: A Comparative Study to Provide Guidance for Wetland Creation and Restoration

Basic Information

Title:	Grant No. 06HQGR0189 Microtopography Effects on Vegetative and Biogeochemical Patterns in Created Wetlands: A Comparative Study to Provide Guidance for Wetland Creation and Restoration
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Descriptors:	
Principal Investigators:	changwoo ahn, Gregory B. Noe

Publication

1. None

Progress report for USGS –NIWR Project

Changwoo Ahn, PI
Environmental Science and Policy
George Mason University

The project involves two-year study of the effects of disking-induced microtopography (MT) on vegetation development and soil nutrients abundance and variability. As of April 28, 2008, we have completed the data collection of microtopographic measurements, vegetation attributes, and soil nutrients and key metals. For Loudoun County Mitigation Bank (LCMB) where we designed specifically 12 plots with 6 disked and another 6 non-disked we have analyzed microtopographic measurements and calculated MT indiced: Tortuosity (T for roughness) and Limiting elevation Difference (LD for relief). We are currently conducting the analysis of vegetation data and lab analysis of soils samples for nutrients and metals. The analysis of entire data will be completed by the end of summer 2008. We will write peer-review papers with the data analyzed from September through the end of project duration (December 2008). In the meantime, we have the first publication out of our microtopography studies:

Moser, KF, C. Ahn, G. B. Noe., 2007. Characterization of microtopography and its influence on vegetation patterns in created wetlands, Wetlands: 1081–1097

Some salaries and supplies for the published work are sponsored by the 2006 NIWR/USGS National Competitive Grant Program (06HQGR0189)

The following provides some preliminary data analysis recently completed:

Table 1. Microtopographic indices for each circular transect scale. T = tortuosity; LD = limiting elevation difference. Scale represents a diameter of the circular transect.

		Non-disked						Disked					
		Cell 1			Cell 2			Cell 1			Cell 2		
	Scale	A	B	C	D	E	F	AA	BB	CC	DD	EE	FF
T	0.5m	1.002	1.001	1.010	1.005	1.003	1.004	1.006	1.008	1.014	1.004	1.024	1.005
	1m	1.003	1.001	1.011	1.004	1.005	1.006	1.008	1.006	1.013	1.008	1.007	1.007
	2m	1.002	1.002	1.011	1.007	1.006	1.007	1.015	1.009	1.016	1.005	1.010	1.009
	4m	1.001	1.001	1.006	1.001	1.003	1.002	1.006	1.003	1.006	1.005	1.003	1.004

LD	0.5m	0.447	0.362	1.007	0.707	0.591	0.821	1.065	1.035	1.591	0.814	1.880	1.131
	1m	1.404	0.467	1.373	1.204	1.005	0.934	2.211	1.920	2.433	1.378	1.654	1.474
	2m	0.818	0.900	2.215	1.499	1.157	1.547	3.268	3.046	2.109	1.640	1.686	2.089
	4m	1.018	1.277	2.104	1.792	1.507	1.344	3.035	3.145	1.983	3.765	1.782	2.606

Table 2. Vegetation attributes for each plots. Mean % cover ± SE; species richness (S_{obs}) as estimated from taxon sampling curves for n = 5 samples ($1m^2$), 50 randomized runs; Shannon diversity index; mean wetland prevalence index (PI) ± SE); FQAI = Floristic quality assessment index; CC = coefficient of conservation; percent within-site similarity (% Similarity) as determined from decomposition of average within-group Bray-Curtis similarity; No. of contributors = number of contributor species for percent within-similarity. Mean percent cover totals of seeded and volunteer taxa may exceed percent cover of overall taxa due to multiple layers of cover.

	Non-disked						Disked					
	Cell 1			Cell 2			Cell 1			Cell 2		
	A	B	C	D	E	F	AA	BB	CC	DD	EE	FF
% cover (overall taxa)	47±4	39±6	77±6	69±6	45±4	14±4	57±5	47±4	86±3	91±3	62±7	82±3
% cover (seeded taxa)	2± 1	1±0	17±7	2±1	44±5	1.5±1	15±3	7±2	16±4	6±3	33±5	6±2
% cover (volunteer taxa)	51±4	41±6	69±8	69±7	13±2	14±3	61±7	54±6	97±7	92±3	48±10	83±4
% cover (invasive species)	2.2±1	0.6±0.5	0±0	0±0	0±0	0±0	2.6±1.2	1.3±1.1	12.3±5.1	0.3±0.3	0±0	0.3±0.3
S_{obs} (overall taxa)	6	3.3	10.6	2.8	2.5	2.2	13.44	12.7	14.6	4	9.4	4.8
S_{obs} (seeded taxa)	1.2	0.7	3.3	0.7	1	0.9	5.3	3.8	2.1	1	2	1.6
S_{obs} (volunteer taxa)	4.3	2	6	1.6	1.5	1.5	8	9	12	2	7	2
S_{obs} (invasive species)	1.1	0.3	0	0	0	0	1.5	0.6	2.2	0.3	0	0.3
H' (overall taxa)	0.6±0.1	0.2±0.1	0.7±0.1	0.1±0.1	0.5±0.1	0.3±0.1	1.7±0.1	1.4±0.1	1.7±0.2	0.2±0.1	1.3±0.4	0.4±0
H' (seeded taxa)	0.3±0.2	0.6±0.4	0.9± 0.2	0.6± 0.1	0±0	0±0	1.2±0.2	0.8 ±0.3	0.8±0.2	0.6±0.2	0.5±0.2	0.3±0.1
H' (volunteer taxa)	0.6±0.2	0.8±0.4	0.6±0.2	0.1±0.1	0.2±0.2	0.1±0.1	1.4±0.	1.5±0.1	1.7±0.2	0.1±0.	1.2±0.4	0.1±0
PI (prevalence indices)	2.8±0 (FAC)	2.98±0 (FAC)	2.9±0 (FAC)	3.0±0 (FAC)	3.7±0.1 (FACU)	3.2±0.1 (FAC)	3.2±0.1 (FAC)	3.0±0.1 (FAC)	2.3±0.1 (FACW)	3.0±0 (FAC)	1.9±0.1 (FACW)	3.1±0 (FAC)
Mean CC	2.83	2.67	3.27	2.67	5	1.5	3.27	3.29	3.54	3.57	3.25	2.5
Number of species*	6	3	11	6	2	2	11	16	13	7	12	4
FQI	6.9	4.6	10.9	6.5	7.1	2.1	14	12.3	12.8	9.5	11.3	5
Average % similarity	66	70	50	70	78	45	48	38	39	81	40	76

Note: *, Number of species with assigned coefficient of conservation (CC) values that were found in study plots; one taxon identified to only genus (Carex sps.) was excluded from the analysis.

USGS Grant No. 08HQGR0004 A Weight of Evidence Screening Value Approach to Nutrient Criteria Development for Wadeable Streams

Basic Information

Title:	USGS Grant No. 08HQGR0004 A Weight of Evidence Screening Value Approach to Nutrient Criteria Development for Wadeable Streams
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Descriptors:	
Principal Investigators:	Tamim Younos

Publication

1. None

Progress Report

A Weight of Evidence Screening Value Approach to Nutrient Criteria Development for Wadeable Streams

Submitted by

Dr. Tamim Younos

March 2008

QUALITY ASSURANCE PROJECT PLAN FOR

NUTRIENT CRITERIA DEVELOPMENT IN WADEABLE STREAMS

Prepared By: Virginia Department of Environmental Quality
Division of Water Quality Programs
Office of Water Quality Programs
Biological Monitoring Program
629 E. Main Street
Richmond, VA 23219

Date: February 1, 2008

A1 Title and Approval Sheet

Name: Gary Du
Title: Quality Assurance Officer

Signature: _____ Date: 2/26/08

Name: Jean Gregory
Title: Project Manager

Signature: _____ Date: 2/26/08

Name:
Title: EPA Grant Manager

Signature: _____ Date: _____

A2 Table of Contents

Figures and Tables

Appendices

A3 Distribution List

Project Manager: Jean Gregory

QA Officer: Gary Du

Regional Biologists: Jeanne Classen, Greg Brown, Warren Smigo, Bill Shanabruch, Mike Shaver, Kelly Hazlegrove, Bill VanWart, Ted Turner, Ed Cumbow, Chip Sparks, George Devlin, Richard Miller

Other Regional Office staff: Jason Hill, Larry Willis, Mark Alling, Bryant Thomas, Greg Anderson, Fred Dilella, Stewart Phipps, Don Kain

Central Office: Patty Walsh, Alan Pollock, Darryl Glover, David Whitehurst, Alex Barron, Aimee Genung, Charles Morgan, Roger Stewart

Water Resource Research Center at Virginia Tech: Tamim Younos

Academic Advisory Committee: Carl Zipper, Len Smock, Tamim Younos

A4 Project/Task Organization

The associated personnel responsibilities for this project are as followed:

Regional Biologists:

1) Perform all field activities including field measurements, observation, and sample collections in accordance with the Quality Assurance Project Plan (QAPP) and Standard Operating Procedures (SOPs).
2) Notify field team leader of any issues encountered.

Field Team Leader

1) Coordinates project activities.

QA Officer

1) Coordinates Quality Assurance (QA) activities to ensure quality in field data, analytical results, and data validity.
2) Conducts field and lab audits on the QA aspects.
3) Recommends corrective actions when necessary.

Project Manager

1) Assures that activities meet the requirements of the project as defined in this project plan.
2) Responsible for development, implementation and management of the project.

A5 Program Definition/Background

EPA has provided funding for this pilot program to develop a screening value approach for nutrient criteria development in wadeable streams. The purpose of this program is to evaluate the ability of the screening value approach to achieve the following intended goals:

1) scientifically and legally defensible criteria that will protect water quality, and
2) can be implemented by the Virginia Department of Environmental Quality (VADEQ) with available resources.

The Academic Advisory Committee (AAC) is recommending that nutrient criteria for freshwater wadeable streams be defined using a screening-value approach. This approach combines a series of water quality and living resource monitoring procedures to determine whether a waterbody is able to support the aquatic-life designated use where nutrient concentrations from routine

monitoring exceed a conservative screening value. The screening value approach is applied with the intention of limiting water quality assessment errors.

A screening value approach is of value because while traditional stressors are generally toxic to organisms, nutrient enrichment effects are systemic. Additionally, the variations in the physical and chemical characteristics of streams also affect organism responses to nutrient enrichment. As a result, biotic responses to nutrient enrichment at specific concentrations are highly variable. The screening-value approach to criteria implementation is recommended as a means of accounting for that variability.

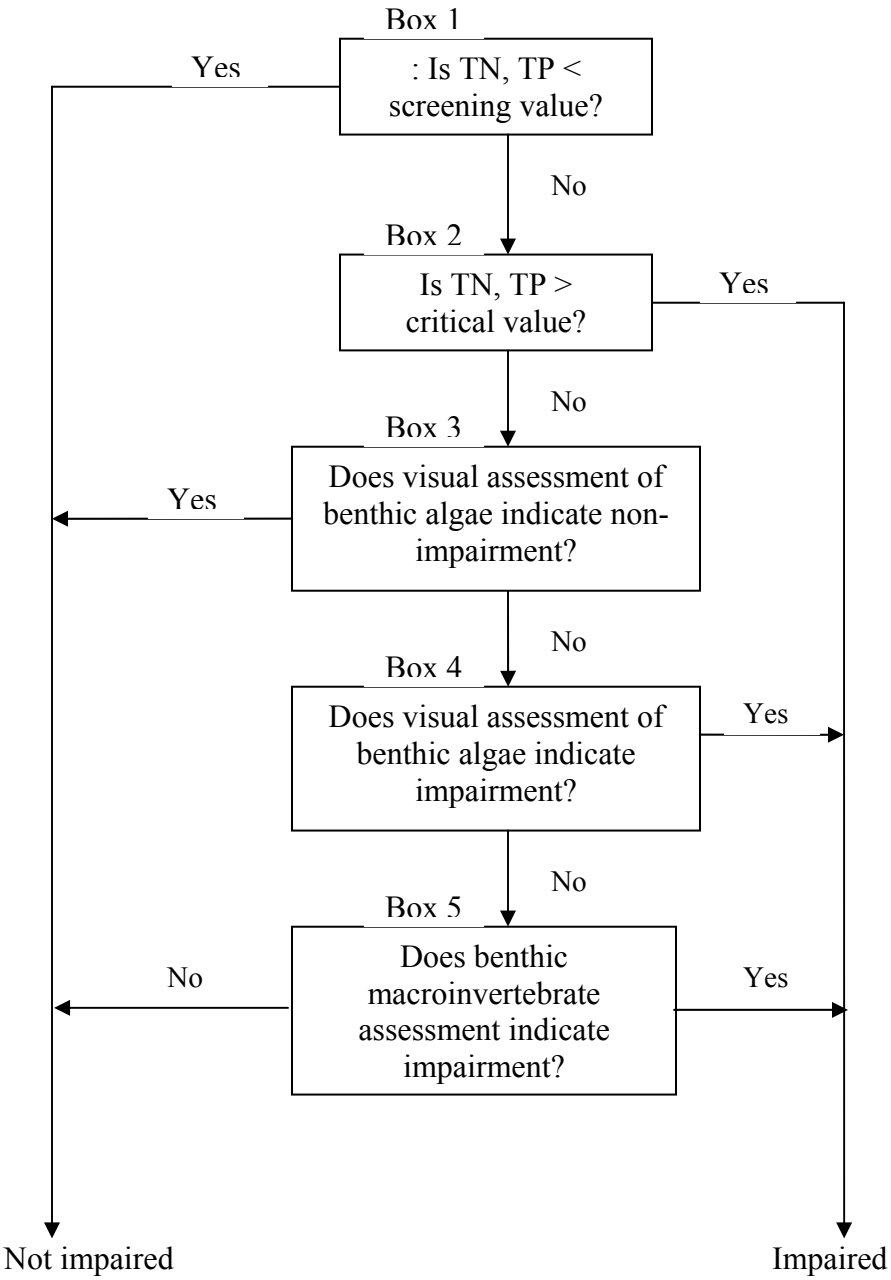
Definition of defensible screening and critical values for use within the proposed nutrient criteria framework (see Figure 1) is integral to program goals. Both goals (1) and (2) above are dependent upon the pilot program's ability to define screening and critical values that are scientifically and legally defensible as components of the nutrient criteria framework (Figure 1, Boxes 1 and 2) while reducing the need for site visitations (Boxes 3 and 4) and benthic macroinvertebrate assessments (Box 5) to levels that can be achieved within VADEQ's resource availability constraints.

Figure 1 (next page) summarizes the proposed approach.

Notes regarding Figure 1. "Screening value" is a concentration above which there is a high probability of impairment (stream condition index < 60) by nutrients, while the "critical value" is a concentration below which there is a low probability of impairment by nutrients. Actual concentrations for N and P critical values and screening values will be determined based on analysis of data generated by the pilot study. The AAC does not expect the screening value and critical value to be identical because non-nutrient factors influence whether or not the stream community becomes impaired at any given nutrient concentration. Preliminary analyses (AAC 2006) indicate that the probability of impairment increases as nutrient concentrations increase, but that definitive impairment designation cannot be made based on nutrient concentrations alone. One purpose for the pilot study is to determine if screening and critical values can be determined with levels of statistical certainty that are adequate for regulatory implementation.

Reference: Academic Advisory Committee (AAC). 2006. December 2006 Report of the Academic Advisory Committee to Virginia Department f Environmental Quality: Freshwater Nutrient Criteria for Rivers and Streams.
http://www.deq.state.va.us/export/sites/default/wqs/documents/AAC_NUT_2006RiversStreamsFinal_000.pdf

Figure 1: Proposed Decision Tree for Nutrient Impairment Designations.



A6 Project/ Task Description

Late summer/fall 2007

Sites to be included in implementation of the spring 2008 pilot program will be selected using the methods described in the sampling process design section. Protocols and forms will be designed

Winter 2008

Academic Advisory Committee, VA DEQ regional biologists, and water quality standards staff meet to finalize sampling procedures and data collection/management.

Spring 2008

VADEQ regional biologists will conduct both a visual assessment and a benthic macroinvertebrate assessment at each of the sites selected. Site attributes relevant to the potential nutrient effects, such as amount of shading (full shade, partial shade, full sun) estimated surface stream velocity (meters/second), stream substrate (sand, gravel, cobble, bedrock, mud), and stream depth and width will be recorded on a field survey form. Biologists will also obtain temperature, pH, dissolved oxygen (DO) and conductivity data and collect the samples for nitrate, total nitrogen, total Kjeldahl nitrogen, ammonia, total phosphorus, suspended solids, turbidity, chlorophyll a and ash free dry mass analyses. Biologists will also apply professional judgment at each site and record observations based on this professional judgment as to the presence or absence of apparent effects on the benthic macroinvertebrate community by non-nutrient stressors. .

Summer 2008

Data from the spring sampling will be assembled and made available to the AAC and to interested parties within VADEQ for analysis. The AAC will review data, meet with regional biologists, and discuss with biologists whether or not midcourse corrections are needed.

Fall 2008

The spring 2008 procedures will be repeated with the new set of sites.

Winter 2008/2009

Data from the fall sampling will be assembled and made available to the AAC and to interested parties within VADEQ for analysis. The AAC (working with other interested parties from VADEQ) will analyze the fall and spring data and summarize the data. The subsequent report will be submitted to EPA in spring 2009. (See Appendix F for graphical timeline representation)

A7 Quality Objectives and Criteria for Measurement Data

A7.1 Data Quality Objectives

Data Quality Objectives (DQOs) are qualitative and quantitative statements that specify the quality of data required to support project decisions. The main objective of this study is to provide a process incorporating monitoring data, visual assessment, and benthic macroinvertebrate community assessment to develop scientifically defensible criteria, which includes the determination of Total Nitrogen and Total Phosphorus values that can serve as screening values and as critical values as well as the levels of uncertainty that would be associated with such designations. The DQOs for this project are provided in Table 1.

The quality of data generated by this project can be expressed in terms of comparability, representativeness, precision, bias, and completeness using the following criteria.

A.7.1.1 Comparability

Comparability refers to the extent to which the data generated by this project is comparable to data collected from the sites from previous studies. To ensure comparability, this project requires the use of standardized sampling and analytical methods, uniform units of reporting, and standardized site selection procedures. The comparability of laboratory data produced for VADEQ is provided by utilizing the state lab where standardized methods are utilized where possible, including EPA approved analytical methods, Standard Methods, USGS Methods, or documented modifications thereof which provide equal or better results.

A.7.1.2 Representativeness

The representativeness of the data is mainly dependent on site selections and the utilization of sampling procedures that produce results adequately representing the true condition of the site sampled. The goal for meeting total representation of the site will be tempered by the types and number of potential sampling points and media as well as the potential funding required for meeting complete representativeness.

A.7.1.3 Precision and Bias

The precision and bias of data are determined by the procedures used by the analytical laboratory and field staff. The precision of data is a measure of the reproducibility of the measurement when the analysis is repeated. It is reported in Relative Percent Difference (RPD). The bias of an analysis is a measure of how much of a constituent actually present is determined. It is measured, where applicable, by adding a known amount of a constituent to a sample and determining how much of the added constituent (spike) is then measured. It is reported as Percent Recovery. The acceptable percent deviations and acceptable percent recoveries are dependent on many factors including: analytical method used, laboratory used, media of sample, and constituent being measured.

A.7.1.4 Completeness

The completeness of data is the relationship of how much usable data are available compared to the total amount of data expected to be available. Ideally, 100% of the data should be available. However, the possibility of data becoming unavailable due to laboratory error, insufficient sample volume, or samples broken during shipment must be expected. Also, unexpected situations may arise where field conditions do not allow for 100% data completeness. Therefore, 95% data completeness is considered sufficient for this project.

Table 1: Data Quality Objectives for Nutrients and Field Parameter

Analyte	Maximum Allowable Bias Goal	Maximum Allowable Precision Goal
Temperature	0.1^{o}C	5%
pH	0.3	105
DO	0.2	5%
Conductivity	1% of range	5%
Turbidity	5% of range	5%
Total Suspended Solids	10%	30%
Total Phosphorus	10%	20%
Total Nitrogen	10%	20%
Ammonia Nitrogen	10%	20%
Nitrate Nitrogen	10%	20%
Total Kjeldahl Nitrogen	10%	20%
Chlorophyll a	20%	30%

A8 Special Training Needs/ Certification

Proper training of field personnel represents a critical aspect of sampling collections. Biologists have been trained and certified to conduct sampling using standardized protocols to ensure comparability in data collection across geographic regions.

A9 Documents and Records

A9.1 Field Data Documentation

The project requires that each data generating activity be thoroughly documented. Field staff record field data on hardcopy field data sheets containing station ID, date and time collected, collector, group code, and the field measurement results. It is recommended that the field data sheets be secured in filing cabinets at the regional offices and maintained for a seven year period. At the end of each sampling day, all the field data are transcribed into the central database (Comprehensive Environmental Data System (CEDS)).

A9.2 Instrument Calibration and Maintenance Documentation

Complete procedures for operating, maintaining and calibrating instruments used in field environmental measurements are contained in water quality monitoring SOPs. Personnel using field instruments are expected to read and be thoroughly familiar with all procedures detailed in the SOPs. A calibration and maintenance log shall be kept for each instrument. Dates of calibration and any other pertinent data shall be routinely entered in the logsheet. All maintenance activities will also be entered in the logsheet. Records shall be maintained for seven years.

A9.3 Laboratory Data Documentation

Documentation for analytical data is kept on file at the participating laboratories and recommended to be maintained on site for five years before being archived at the state library. Documents should be readily available for review during external audits and should include the analyst's comments on the condition of the sample, progress of the analysis, primary standard certification, working standard preparations, instrument calibration results, results of QC check sample/measurements or instrument printouts, and final data calculations.

B1 Sampling Process Design

Site Selection:

The sites for this pilot project will be selected using the following methods:

1. Site is existing water quality monitoring station that is in current operation.

2. Site is represented by recent water-quality data so it can be placed reliably within a nutrient category.

3. Site is wadeable and suitable for benthic macroinvertebrate sampling. (Given that the biologists have other demands, the selection process would emphasize stations where the benthic macroinvertebrate assessments are scheduled for other purposes when such stations meet the Pilot Program's other requirements.).

4. Site is not known to be subject to major influence by non-nutrient stressors (urban runoff, toxics, sediments, point source discharges, etc.) that would cause benthic impairment.

5. Each region selects approximately 12 sites from the list of stations prepared (approximately 6 sites for sampling in the fall and 6 for sampling in the spring) with a total of 62 sites selected for pilot study.

- At least one station within each of the 6 N-concentration categories, and at least one station within each of the 6 P-concentration categories, should be represented. Those categories are in Table 2. (Note: because each station is placed in both an N-concentration category and a P-concentration category, this condition can be met with fewer than 12 sites).

- To the extent possible: For the lowest N-concentration category (1), assure that relatively low, medium, and high P concentrations are represented; and for the lowest P-concentration category, assure that relatively low, medium, and high N concentrations are represented.

Table 2 Total Nitrogen and Total Phosphorus Concentration Categories

Category	TN Concentration Range (mg/L)	TP Concentration Range (mg/L)
1	<0.5	<0.02
2	0.5 - <1.0	0.02 - <0.04
3	1.0 - <1.5	0.04 - <0.06
4	1.5 - <2.0	0.06 - <0.10
5	2.0 - <3.0	0.1 - <0.20
6	>=3.0	>=0.2

6. Choose sites that are not clustered geographically or fluvially, and thus are distributed throughout the entire region.

B2 Sampling Methods

Nutrient sample collection:

Three 1 qt. cubitainers grab samples will be collected approximately three inches below the surface of the water. The monitoring staff wade in the stream and approaching the sample site from downstream to avoid stirring up the sediment. Cubitainers are rinsed in the stream and discard the rinsate in the downstream direction. The cubitainer is lowered into the stream at the centroid of the greatest flow (area where the flow is equal on the right and left side) and is filled taking care not to disturb the streambed to prevent the sediment from entering into the container. One cubitainer is labeled with a group code of "T2", another with "INUT2" and the third container is preserved with 1 ml concentrated Sulfuric Acid and labeled "INUTL". All containers are preserved with wet ice in a cooler.

Chlorophyll a and Ash Free Dry Mass sample collection is described in Appendix A. The sample collection protocol checklist for regional biologists is provided in Appendix B. Benthic macroinvertebrate sample collection and assessment will be done according to established VADEQ protocols as detailed in the VADEQ Biological Monitoring of Virginia Quality Assurance Project Plan for Wadeable Streams and Rivers (Appendix C) or its successor

document. Field personnel will fill in the required information on the Nutrient Criteria Visual Assessment Field Form (Appendix D.).

B3 Sampling Handling and Custody

In the field, all samples will be packed in wet ice after collection and during shipment so that they will be kept at approximately 6^{o}C. Sample containers will be clearly labeled with printed labels or sample tags. All caps and lids will be checked for tightness prior to placement in the cooler. Field staff will drain the water from the cooler at the end of sampling day and refill the cooler with ice to maintain the samples at 6^{o}C. Samples are shipped in the cooler overnight to the Division of Consolidated Laboratory Services (DCLS) via contract courier service. Upon receipt of the samples, DCLS will check the information on the labels against the information field staff has entered into CEDS. If the information does not match, the lab staff will try to reconcile the differences or reject the sample(s). DCLS will also measure the temperature of the samples using a temperature bottle kept in the cooler throughout the collection and shipment process and acidified samples for pH. If the measurements exceed the limits, the lab qualifies the sample result or rejects the sample. Once the samples have been logged, the lab staff will transfer them to the refrigerator and store them at 4^{o}C. All samples will be handled, prepared, transported and stored in a manner so as to minimize bulk loss, analyte loss, contamination and/or biological degradation.

Ideally, all analyses are completed within a few days after processing to allow for review of the results and possible reanalysis of suspect samples within fourteen days. Critical holding times for the analyses are the maximum allowable holding time base as defined by EPA and Standard Methods.

Formal chain of custody procedures are not required for this project as the water monitoring data are not intended to be used as admissible evidence to enforce the Commonwealth's environmental laws and regulations (see the Virginia Department of Environmental, Quality Division of Water Quality Programs Guidance Memo No. 03-2003, Amendment #1 Interpretation for Water Monitoring of Guidance Memo No. 00-2016 Chain of Custody Policy and Procedures at: (http://www.deq.virginia.gov/export/sites/default/waterguidance/pdf/032003a.pdf).

B4 Analytical Methods

The analytical methods used by DCLS for this project are in accordance with currently approved procedures given in Standard Methods for Examination of Water and Wastewater or EPA Methods for Chemical Analysis of Water and Wastes. DCLS analytical methods are described in Table 3. A detailed description of analytical procedures and the instruments used for each analysis are included in the laboratory's Standard Operation Procedures.

Table 3: Analytical Methods for the Project

Parameter	Analytical Method
Nitrate Nitrogen	EPA method 353.2
Ammonia Nitrogen	EPA method 350.1
Total Nitrogen	SM 4500 N Part C
Total Kjeldahl Nitrogen	EPA method 351.2
Total Phosphorus	EPA method 365.4
Total Suspended Solids	SM 2540 B
Chlorophyll a	SM 10200 H
Ash Free Dry Mass	SM 10300 C
Turbidity	SM 2310 B

B5 Quality Control

B5.1 Quality Assurance Objective

Measurement quality objectives (MQOs) are listed in Table 5. The MQOs given in Table 5 represent the maximum allowable criteria for statistical control purposes.

For duplicate samples, precision across batches is estimated as the pooled standard deviation of all samples at the lower concentration range, and as the pooled percent relative standard deviation of all samples at the higher concentration range. Bias (systematic error) is reported as net bias. Net bias is estimated as the difference between the mean measured value and the target value of a performance evaluation and/or internal reference samples at the lower concentration range measured across batches. Precision and bias are monitored at the point of measurement (field or analytical lab) by several types of QC samples described in the Section B.5.3.

B5.2 QC Procedures for Field Operation

For in-situ measurements, each field instrument must be calibrated prior to use and calibration information should be recorded on a calibration logsheet. A calibration logsheet is maintained by each regional office for every piece of field instrument. The field instrument should be checked at the end of each sampling day for drift in calibration. The acceptance criteria for the drift of field parameter are listed in Table 4.

Table 4: Acceptance Criteria for Field Parameters

Check Description	Acceptance Criteria
DO	±0.5 mg/l
pH	± 0.2 unit
Conductivity	±10%
Verify performance of temperature probe	Functionality ± 1^{o}C

Field QC Samples;

Field staff will collect equipment blank and field split samples at a rate of 10% of the total samples collected. Acceptance criteria for the field QC samples are listed in Table 5.

B5.3 QC Procedures for Laboratory Operation

QC protocols are an integral part of all analytical procedures to ensure that the results are reliable and analytical stage of the measurement system is maintained in a state of statistical control. Information regarding QC sample requirements and corrective actions are summarized in Table 5.

Table 5: QC Sample Requirements and Corrective Actions

QC sample type	Frequency	Acceptance Criteria	Corrective action
Equipment blank	10% of total samples	Not to exceed of three times of the MDL	Determine cause of problem, remove sources of contamination , and reanalyze all suspect samples or flag all suspect data
Field split samples	10% of total samples	RPD< 30%	Prepare and analyze lab split sample, review precision of QC sample measurement. Check preparation of split sample. Qualify all samples in batch for possible reanalysis.
Laboratory method blank	One method blank per analytical batch	Not to exceed three times of the MDL	Prepare and analyze new blank. Determine and correct problem before proceeding with any sample analyses.
Calibration check standard	Before and after sample analyses	± 10% of true value	Repeat QC samples. Recalibrate and analyze QC samples.
Standard reference material	One per analytical batch	Manufacturers certified range	Analyze the standard in the next batch to confirm suspected imprecision or bias. Evaluate calibration and

			QC samples and standards for contamination and preparation error. Qualify all sample batches analyzed since the last acceptable reference standard measurement for possible reanalysis.
Lab duplicate sample	One per batch	Control limit < precision objective	Prepare and analyze duplicate from different sample. Review precision of QC sample measurements. Check preparation of duplicate sample.
Matrix spike sample	One per batch	Can not exceed 100 ± 10%	Select two additional samples and prepare fortified subsamples. Reanalyze all suspected samples in batch by the method of standard addition.

B6 Instrument/Equipment Testing, Inspection, and Maintenance

To minimize downtime of the measurement system, all field and lab instruments must be maintained in working condition. Environmental field specialists and lab technicians will inspect instruments and equipment daily. Corrective action will be taken immediately when problems are found. Backup instruments/equipment or common spare parts will be available so that if any piece of instrument fails during use, repairs or replacement can be made as quickly as possible and the measurement tasks resumed. Preventive maintenance should be performed according to the manufacturer's recommendations.

B7 Instrument/Equipment Calibration and Frequency

Field and lab instruments and equipment require routine calibration checks to verify that their performance is within acceptable quality standards. The following sections will discuss procedure and frequency for the instrument calibrations.

B7.1 Field Operations

Each field instrument must be inspected prior to use and calibrated with standards bracketing the expected concentration of the samples.

B7.2 Laboratory Operations

Calibration of the lab's analytical instruments is required to assure that the data generated meet Data Quality Objectives (DQOs). Detailed calibration frequencies and acceptance criteria are specified in the analytical method SOPs. Calibration activity performances are documented and are available for review during internal and external lab audits.

In general, reference standards used will bracket the expected concentration of the samples. At a minimum, this generally will require the use of three to five different standard concentration levels to quantitate the instrument's linear range. Calibration of the instruments must be performed prior to sample analyses and then at periodic intervals during the analyses to verify that the instruments are still in calibration. Sample concentrations exceeding the calibration ranges need to be diluted and reanalyzed.

B8 Inspection/Acceptance of Supplies and Consumables

This project will only utilize supplies and consumables that are of adequate quality to sustain confidence that data generated in the sample collection; processing and laboratory analyses will meet the DQOs. Purchased supplies and consumables will not be used until they have been inspected, calibrated, or otherwise verified to ensure compliance with any relevant standard specifications for use in this project.

B9 Non-Direct Measurements

This project's data will primarily be generated directly through field measurements and laboratory analyses. No indirect measurements will be used for this project.

B10 Data Management

Constituents measured in the field are recorded manually on a field data sheet and entered by the field specialist into CEDS upon returning to the office. The CEDS system has been designed to prohibit obviously incorrect data from being entered. Field data sheets will be kept in the file for five years.

Once the analytical results have been verified and validated by lab personnel, they are loaded into the CEDS database via an automated File Transfer Protocol (FTP). Laboratory files processed by the system are archieved on the server to retain the original data files.

Retrieval of the data can be accomplished through a web interface. Users can download the data to their computers for use in a spreadsheet, running customized reports, processing customized queries, or simply review the data through a browser window. VADEQ Central Office staff will query the CEDS system for lab and field data relevant to this pilot project and provide it to the AAC.

Benthic macroinvertebrate assessment results will be handled in a manner similar to DEQ's standard biological monitoring activity: raw scores for family groups will be determined and converted into metrics commonly utilized by VADEQ including the Stream Condition Index. These data will also be entered into the Ecological Data Application System 2.1 (EDAS) where they will be retrieved by VADEQ Central Office staff and provided to the AAC.

C1 Assessment and Response Actions

C1.1 Field Crew

Field staff are trained by the QA Officer and follow the Water Quality Monitoring Program's Standard Operating Procedures (SOP) to ensure the consistency between regions.

C1.2 Field Reviews

To ensure that actual field collections are conducted in accordance with SOP, the performance of field staff will be evaluated by the QA Officer. The format for the evaluations will be more of a field procedural review than audit. The goal is to conduct at least one collection activity review during the whole project. The evaluator will use an approved checklist to systematically document acceptable/unacceptable performance on all pertinent aspects of the sampling.

Any minor deficiencies observed during a field procedure review should be immediately pointed out to the staff and corrective actions imposed on-the-spot. If significant deficiencies are observed, the evaluator will make the appropriate on-the-spot correction, and if the case warrants, stop the field activities until the problems are resolved to the satisfaction of the QA Coordinator. All cases of this nature will be documented.

C1.3 Laboratory Activities

Internal and external audits are conducted regularly at DCLS to monitor the overall effectiveness of the quality assurance system. Internal audits are performed by the QA

department, which is responsible for all QA/QC functions in the laboratory, and/or members of the professional laboratory staff that do not normally work in the section or analytical unit being audited. External audits are conducted by the persons who are not direct employees of DCLS to provide an independent and unbiased review of laboratory operation.

There are two types of audits: system audits and performance audits. 1) System audits involve an in-depth review and evaluation of some or all of the components of the analytical laboratory to determine if guidelines listed in the QA plans are properly applied. 2) Performance audits require the analysis of blind samples or other samples whose values are not known to the analytical lab. These results are used to evaluate the accuracy of the lab analytical system.

C1.3.1 System Audit

1) System Internal Audits

The QA department conducts several system audits each calendar year. During these audits, one or more components of the lab will be reviewed to determine if that part is functioning in compliance with the lab QA plan, the approved SOPs, and approved methodologies. An audit report will include a list of deficiencies that must be addressed in order to correct or improve the lab operations.

System components to be audited during the internal audit will include, but are not limited to:

- All documentation associated with sample and data handling, to include linkage mechanism employed between all records for tracking documentation for any sample data result.
- Use of established approved procedures as outlined in the QA plan.
- Personnel training records
- Proper execution of established procedures.
- Follow-up to corrective actions from previous audits.
- Sample and data handling activities: all sample login, routing and disposal; sample preparations; method calibrations; sample analyses; data reduction, validation and reporting; preventative maintenance and repair procedures; standard and reagent preparation, documentation and storage; sample and waste disposal; container and labware decontamination; QC management practices and assessment of analytical precision, accuracy and sensitivity.
- Deficiency lists and associated corrective action orders will be formally communicated to responsible staff.

2) System External Audits

External audits are performed when certifying agencies or clients submit samples for analysis and/or conduct on-site inspections. External laboratory systems and performance audits are

conducted by VADEQ. The VADEQ WQM QA team is responsible for conducting external laboratory audits of each division at least biannually.

C 1.3.2 Performance Audit

The laboratory is involved in external performance audits conducted annually through the analysis of performance evaluation samples provided by the QA department or third party.

The QA department and VADEQ conduct performance evaluations using commercially prepared samples as blind samples. The results of these audits will be documented and reported to managers so that any necessary adjustments can be made.

Blind sample audits are performed by submitting QC samples to the analyst. The true values are only made known after the test is completed. Blind sample audits are carried out by the QA department, clients and certifying agencies as necessary to assure the lab is capable of achieving success with a blind QC sample.

C2 Reports to Management

C2.1 Field Activities

The field team leader should update the progress on the general status of the field team's activities on a regular basis to the project manager. These updates can be informal and be communicated by telephone or e-mail.

C2.2 Final Report

The QA Officer will prepare the data assessment and final report to the project manager when the project is completed.

D1 Data Review, Verification, and Validation

The most critical component of data review, validation and verification of data generated in this project will be conducted by staff at the regional offices and laboratory staff when it is generated through the analytical results. The overall data quality of each parameter will be evaluated in terms of accuracy and precision by the QA Officer using the quality criteria described in this QAPP (see section B5.3). Data sets that meet all the prescribed quality criteria will be accepted without further qualification for use in development of nutrient standards. Data that do not meet all of the acceptable criteria because of minor deficiencies will be assigned data qualifier codes

to flag them as questionable values. These data may still be included in the data set to allow the data users to decide for themselves whether the data are acceptable for their specific purpose. Data that consistently fail one or more quality criteria assessment by a significant margin will be rejected and deleted from the data set.

D2 Verification and Validation Methods

D2.1 Data Verification

Data verification is a process of evaluating the completeness, correctness and conformance/compliance of a specific data set against the cited method, procedure or expected results.

Field data verification should include: a review of data for correctness, use of correct units, data reality in relation to the range of expected results, and data completeness. For example, an evaluation needs to be conducted for transcription errors that occur when transcribing the information from field data sheets into electronic format. This evaluation will be performed on the randomly selected sites for a total of at least 10% of all stations.

When lab results are transmitted to the VADEQ CEDS database the QA Officer will conduct the verification process as follows:

1) Each result will be compared to historic data collected from the same site. The datum will be flagged if it falls more than three standard deviations from the mean for a given parameter.
2) The values of split samples will be flagged if the coefficient of variation of the difference in the split samples exceeds 20%.
3) The datum will be flagged if the holding time was exceeded.
4) If internal logic checks (the sum of individual species is greater than total concentration) are violated, then all results involved will be flagged.

D2.2 Data Validation

Data validation is an analyte and sample specific process that extends the evaluation of data beyond method or procedure to determine the analytical quality of specific data set.

Measurements of field parameters taken directly in the field will be evaluated for accuracy by verifying the results by calibration and checking for instrument drift. These checks should be performed by the field staff on a daily basis and, if the instruments are out of specifications, they should be recalibrated. Any field data that was collected while the instrument was out of compliance will be removed from the database.

The QA Officer will be responsible for conducting data validation of the data before submitting the data to project manager. The data set will be assessed by a critical comparison of the submitted QA/QC results to the quality criteria or standards established by this QAPP for that analysis. If the evaluation indicates that the data meet the quality standards overall, with no or only minor deficiencies, then the data set will be considered acceptable for the project without further qualification. If the data consistently fail one or more quality criteria then the data set will be flagged with an appropriate data qualifier code. Depending on the degree of the deficiency, the data might still be used for some purpose or may be removed entirely from the database.

D3 Reconciliation with User Requirements

Samples collected in this project will be subsequently analyzed and used for developing nutrient standards. It is essential that the data quality is at the highest level. Data rejected during laboratory analysis or during the data validation process are considered unusable. It is recommended that the samples should be reanalyzed or additional samples should be collected.

Appendix A: Field Sampling Procedure for Chlorophyll a and Ash Free Dry Mass (AFDM) Sample

For each sample select 3-5 rocks from the sample reach (approximately 300-400 sq cm). Each set of 3-5 rocks will constitute one composite sample. Select rocks from the main part of the river, avoiding areas very near the shore, if possible. Avoid heavily shaded areas; select un-shaded sites if possible. Rocks should be 10 to 25 cm in greatest dimension and representative of other rocks in the reach; select from different sections in the sampling reach. If there are no larger rocks, select 5-10 smaller rocks. A good strategy would be to select six to eight rocks, randomly, then keep the three to five that are most representative. Put the selected rocks in a plastic tray. Scrape all algae from the rocks using nylon brushes, scalpel, knife, or spoon. Use a fine spray from a squirt bottle (filled with clean river water) to wash algae from rocks. Use scissors to cut non-diatom filamentous algae into pieces no longer than 0.25 to 0.5 cm. Remove sand from the sample by floating. Pour the sample from the tray into labeled amber bottle. **When only fine sediments are present**, algae should be sampled using a plastic bottle with the bottom cut off and a flat piece of plastic. Place the bottomless bottle into the substrate and depress 1 inch into the sediment. Place a piece of flat plastic under the lid to seal the bottom and remove from the river. Pour the sediment into a tray and float the algae off of the sand and rinse into a sample container.

Sample Processing: Samples should be homogenized in the amber bottle by shaking vigorously. The sample is then poured into a 1000ml graduated cylinder, and brought to a constant total volume with DI water that is easily divided by two. The sample should then be subdivided into two containers, one for chl *a*, and one for AFDM analyses. Ensure that the sample is well mixed before measuring sub-samples. Transfer about 500 ml of sample to amber bottle for AFDM analysis and add two mls of saturated magnesium carbonate the chlorophyll sample. **Keep samples in dark and cool.**

Outlines and Field Notes: The foil outline represents the surface area of the rock sampled. Wrap aluminum foil around the sampled surface of each rock. Press foil tightly to rocks following the curved surface. Either trim the bottom edge with scissors or fold excess foil upwards. Remove foil from the rock and make radial cuts in foil to allow the foil to be flattened. Place each foil on paper and trace the outline. It is preferred that the flat rock outline fit within the limits of an 8.5 x 11 sheet of paper. **Label each page with site name, date, number of rocks collected from each site, and initials of the person making outline**. For fine sediment samples, trace one bottle outline and note the number of samples in the bottle. Store foil, and rock outlines in a large envelope. Original rock outlines should be kept in the regional office. Scanned electronic copies will be sent to WQS in central office.

Appendix B: The sample collection protocol checklist for regional biologists

Before Site Visit:

_____ 1. Divide total number of stations into two sampling periods: Spring 2008 (March 1 until mid June) and Fall 2008 (September 1 until mid November).

_____ 2. To maximize the number of stations sampled during this trial, do not schedule repeat visits to a previously sampled station.

_____ 3. Schedule assessments under "base flow conditions" and not until 14 days after a "scouring rain event" (90th percentile USGS stream gauge flow or BPJ) has occurred.

_____ 4. Schedule with DCLS prior to each site visit: one sample for INUTL and INUT2, a second half gallon sample to submit as T2 group code T2 and a sample for CHLBEN.

During Site Visit:

____ 1. Collect all screening protocol data, including macroinvertebrates, at each station.

____ 2. Collect replicate samples for INUTL, INUT2, T2, and CHLBEN (but not macroinvertebrates) at one station during the study for purposes of QA/QC.

____ 3. Conduct visual assessment and record observations on survey form.

____ 4. Collect one water sample for INUTL and INUT2 and a second half gallon sample for the T2 group code.

____ 5. Collect periphyton scraped off rocks for ash-free dry mass and chlorophyll *a* for CHLBEN analysis using probmon procedures, including the preparation of aluminum foil template of the surface area scraped.

____ 6. Take the following field measurements and record on the Nutrient Criteria Visual Assessment Field Form:
_____ Temperature - In-Situ, YSI or Hydro-Lab multi-probe meter (verified with NIST thermometer in lab).
_____ pH – In-Situ, YSI or Hydro-Lab multi-probe meters (calibrated and post-confirmed checked each field day, using commercially available standards)
_____ Dissolved oxygen –In-Situ, YSI or Hydro-Lab meter (pre-calibrated and post-confirmed each field day, using (100% RH) air standard)
_____ Conductivity- In-Situ, YSI or Hydro-Lab meter (calibrated and post-confirmed each field day, using commercially available standards)

Post Site Visit:

____ 1. Email station ID and the corresponding DCLS lab number for parameters utilized in this Pilot Program to dcwhitehurst@deq.virginia.gov when those lab numbers are received.

_____2. Schedule processing and analysis of macroinvertebrate samples so SCI scores will be available through EDAS by project reporting deadline.

____ 3. Email a scanned electronic image file and associated sample site information (station ID, date, staff name) of surface area sampled needed for calculation of chlorophyll *a* to: David C. Whitehurst at VADEQ Central Office (dcwhitehurst@deq.virginia.gov).

____ 4. E-mail a scanned copy of the Nutrient Criteria Visual Assessment Field Form field sheet as a PDF file to Dr. Carl Zipper (czip@vt.edu) by reporting deadlines of July 15, 2008 for stations sampled in the Spring and December 15, 2008 for stations sampled in the Fall.

Appendix C: Virginia Department of Environmental Quality Biological Monitoring of Virginia Quality Assurance Project Plan for Wadeable Streams and Rivers

BIOLOGICAL MONITORING PROGRAM

QUALITY ASSURANCE PROJECT PLAN FOR

WADEABLE STREAMS AND RIVERS

Prepared By: Virginia Department of Environmental Quality
Division of Water Quality
Office of Water Quality Programs
Biological Monitoring Program
629 E. Main Street
Richmond, VA 23219

Date: January 11, 2008

Group A: Project Management Elements

A1 – Title and Approval Sheet

Virginia Department of Environmental Quality
Biological Monitoring of Virginia
Quality Assurance Project Plan for
Wadeable Streams and Rivers

*Approved via email (on file)*_____
Frank Ciambrano Date:
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Phone: (215) 814-5746
EPA Project Officer

*Approved via email (on file)*_____
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Ph.D., Director, Division of Water Quality Programs

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Manager, Water Quality Monitoring and Assessment Programs

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Gary Du Date:
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QA/QC Coordinator

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Aimee Genung Date:
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Biological Monitoring Program Coordinator

A2 – Table of Contents

Element/ Section

FIGURES

TABLES

A3 – Distribution List

Name	Organization
Frank Ciambrano	U. S. Environmental Protection Agency, Region 3
Larry Merrill	U. S. Environmental Protection Agency, Region 3
Ellen Gilinsky	Virginia Department of Environmental Quality
Darryl Glover	Virginia Department of Environmental Quality
Gary Du	Virginia Department of Environmental Quality
Aimee Genung	Virginia Department of Environmental Quality

Other staff from Virginia Department of Environmental Quality as appropriate.

A4 – Project/ Task Organization

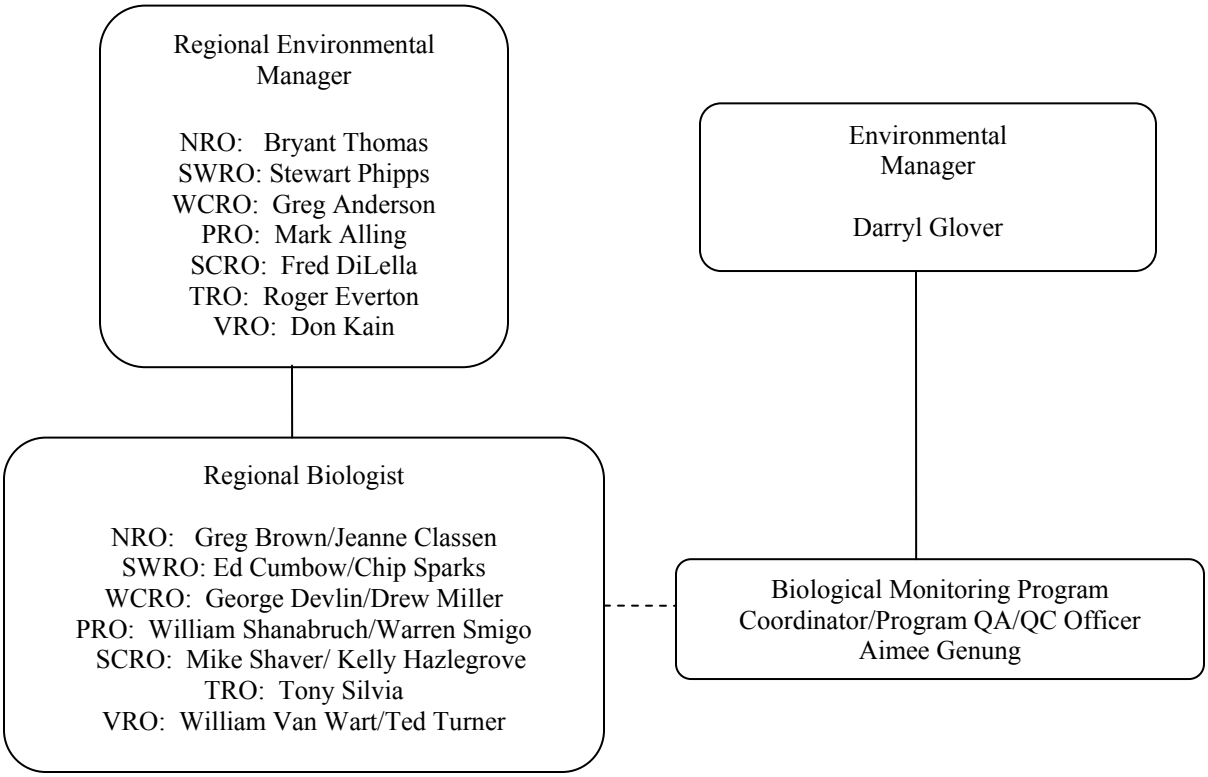


Figure 1: Organizational Chart for VADEQ's Biological Monitoring Program

Virginia Department of Environmental Quality's (VADEQ's) freshwater biological monitoring program is conducted out of seven regional offices located throughout Virginia. These offices are located in Abingdon (Southwest Regional Office), Roanoke (West Central Regional Office), Lynchburg (South Central Regional Office), Harrisonburg (Valley Regional Office), Woodbridge (Northern Regional Office), Glen Allen (Piedmont Regional Office), and Virginia Beach (Tidewater Regional Office). With the exception of TRO, each regional office is staffed with two regional biologists under the direction of the regional environmental manager (Figure 1). The biological monitoring program coordinator in the VADEQ's Central Office in Richmond is responsible for the coordination of the biological monitoring program and also serves as the program QA/QC officer. The program coordinator is under the direction of the environmental manager in the Richmond Central Office.

A5 –Background

Virginia's freshwater biological monitoring program began in the1970's to fulfill requirements of the Federal 106 grant agreement. VADEQ uses benthic macroinvertebrate communities to assess the ecological health of freshwater streams and rivers. Benthic macroinvertebrates are larger-than-microscopic invertebrate organisms such as insects, crustaceans, snails, mussels, or worms that inhabit stream bottoms.

VADEQ's biological monitoring program examines over 150 stations annually. Reasons for bioassessments include, but are not limited to: targeted monitoring, probabilistic monitoring, tracking local pollution events, follow-up on waters of concern identified through volunteer citizen monitoring, and TMDL monitoring. Data from the biological monitoring program are used in the periodic review and assessment of state waters as required by Section 305(b) of the Clean Water Act. Benthic macroinvertebrate monitoring is used in assessing the designated use of state waters established in 9 VAC 25-260-10 A. that states in part that "All state waters, including wetlands, are designated for the following uses: ……the propagation and growth of a balanced, indigenous population of aquatic life, including game fish, which might reasonably be expected to inhabit them….." .

Biological monitoring using benthic macroinvertebrates is an invaluable tool for evaluating the overall, temporally integrated effects of the water and sediment quality in streams and rivers. Benthic macroinvertebrate communities indicate water quality both over time and the effects of different pollution stressors, thus providing a measure of their collective impact, including antagonism and/or synergism among chemical and physical pollutants. Because of their sedentary nature, macroinvertebrates are good indicators of localized conditions. Most species have a complex life cycle of approximately one year or more and, therefore, integrate the effects of fluctuations in water quality over time, which periodic, conventional water quality surveys may miss. In essence, benthic macroinvertebrates are considered to be virtual "living recorders" of water quality conditions over time. The structure and functioning of macroinvertebrate communities are also extremely sensitive, and may exhibit responses to water quality parameters for which specific criteria or standards have not been defined, for which chemical analyses are not normally performed, or for which biological tolerance is below chemical detection limits.

The VADEQ uses two bioassessment indices to assess the biotic integrity in non-tidal freshwater streams and rivers in Virginia. In the Coastal Plain, which is characterized by low gradient streams east of the fall line, the Coastal Plain Macroinvertebrate Index (CPMI) is used. This multimetric bioassessment index was developed in 1997 by the Mid-Atlantic Coastal Streams (MACS) workgroup (USEPA 1997 and Maxted et al. 2000). The CPMI was calibrated for low gradient Coastal Plain streams, which exhibit different expected benthic macroinvertebrate communities from non-coastal streams.

For non-coastal streams, biological assessment of the benthic macroinvertebrate community is based on the methods of the Virginia Stream Condition Index (VSCI). The VSCI was developed for Virginia freshwater non-coastal streams by USEPA's contractor Tetra Tech, Inc., using historical data collected in Virginia at reference and stressed streams in 1994-1998, and was tested against additional data collected in 1999-2002. This review has resulted in the development of the Virginia Stream Condition Index (VSCI) for use in assessing wadeable, non-coastal streams. The VSCI is based upon recent advances in bioassessment methods contained in "*Rapid Bioassessment Protocols for Use in Wadeable Streams and Rivers, Second Edition*" (Barbour et al. 1999). The VSCI, a multimetric calculation of benthic integrity converted into a single numerical score, resulted in a single reference condition for the entire non-coastal portion of the Commonwealth against which all future benthic samples will be compared. The development of this index is considered a significant step in the advancement of the biomonitoring program to address a wide range of monitoring and assessment needs. Based on recommendations from public comment and the

Academic Advisory Committee (AAC), the VSCI was validated using a spatially diverse (ecoregionally and stream size) data set free of pseudoreplication (http://www.deq.virginia.gov/probmon/) These probabilistic data sets have allowed VADEQ to narrow data gaps, test the VSCI against many classification variables and confirm with certainty that the VSCI is a good assessment tool for Virginia streams.

The 2008 Integrated Report will be assessing the biological data using the VSCI and the CPMI in the 305(b) report. VADEQ finalized this Stream Condition Index in 2006 and this will be the first report that uses the VSCI to assess the biological data.

A6 – Project/ Task Description

The VADEQ Data from the biological monitoring program are used in the periodic review and assessment of state waters as required by Section 305(b) of the Clean Water Act. The following are the primary data uses:

1. 305(b) reports: Data are used to provide water quality assessments for the biennial 305(b) reports to the U.S. EPA and Congress.

2. 303(d) listing: All stream segments assessed as severe stress and those where repeated sample data confirm stress are listed on the 303(d) list of waters prioritized for TMDL development and remediation activities.

3. Virginia Pollutant Discharge Elimination System (VPDES) permits: Some data are used in the permitting process. Biological Assessment Reports may determine if an existing discharge permit is protective of the resident fauna. If the discharge is found to impair the benthic macroinvertebrate community, the permit may be recommended to be reviewed.

4. Probabilistic monitoring (ProbMon): The ProbMon network is a set of randomly chosen stations used to make statistically-based assessments of Virginia's streams.

5. Tracking local pollution events: Biological data may be used to determine the effect of local pollution events in streams and to track the rate of recovery of the benthic communities in these streams.

6. Exceptional State Waters designation: Benthic macroinvertebrate data may be used to determine the exceptional aquatic communities eligibility criterion of Virginia streams and rivers to be classified as "Exceptional State Waters" (9 VAC 25-260-30 (3)).

Stream Macroinvertebrate Sampling

VADEQ uses two sampling procedures for benthic macroinvertebrates depending on stream geomorphology and instream characteristics. The single habitat sampling approach is used for streams in which riffles with appropriate substrate (cobble) are available for sampling and are large enough so that at least 2m² of the substrate can be sampled. The single habitat sampling approach is used exclusively in high gradient streams (see Appendix B i). The multihabitat sampling method is used in cases where no riffles are present, the riffles in the reach are too small and/or too few to sample 2m² of substrate. These riffles are, however, candidates for sampling using the multi-habitat method if they represent at least 5% of the available substrate (see Appendix B ii). Multi-habitat sampling is most commonly performed in, but not limited to, low gradient streams.

Habitat Assessment

Habitat assessment is conducted at each bioassessment site. Both in-stream and riparian habitat are important determinants of the composition, structure, and function of macroinvertebrate communities. Habitat quality is often an indicator of water quality stressors in streams. In addition, poor habitat quality can obscure the effects of specific pollutants. A systematic assessment of in-stream and riparian habitat quality is necessary to fully assess water quality conditions in streams and rivers.

Habitat assessment is considered an important tool for the final evaluation of impairment. Habitat parameters that are evaluated are related to the overall aquatic life use and are a potential source of limitation to the aquatic biota. Both the quality and quantity of available habitat can affect the resident biological community structure and composition. The final conclusion of a bioassessment should take into consideration the habitat quality of a water body and whether the health of aquatic biological communities is limited by habitat conditions. Procedures for habitat assessments are located in Appendix B (iii).

Physicochemical Parameters

Physicochemical parameters, including Dissolved Oxygen (DO), pH, specific conductivity, and temperature, are collected at each site using several different types of multi-probe meters. These parameters may provide valuable information in determining what water physicochemical characteristics may be limiting to the health of aquatic biological communities.

Reference Site Selection

Due to the rarity of "pristine" waterways, reference sites are considered to be stream reaches that are the "least disturbed," or are considered to be in the best available condition for a certain ecoregion. Ecoregions are defined as being contiguous land forms with similar geology, soils, vegetative cover, and climate and it is hypothesized that biotic communities within ecoregions are likely to be similar. Reference sites are not needed for VSCI or CPMI assessments, but may aid in future revalidation of these indices.

Reference streams are determined in part by using data from land cover, water quality, and habitat surveys. Biologists BPJ may also be used to determine if a stream has any legacy pollution issues that may result in the stream not meeting the reference requirements.

A7 – Data Quality Objectives

High quality data is imperative to the VADEQ's biological monitoring program's ability to accurately assess the condition of Virginia's streams and rivers. The specific data quality objectives, as discussed below, include accuracy and precision, representativeness, and comparability.

Accuracy and Precision

Data quality objectives for this program emphasize accuracy and precision of benthic macroinvertebrate identification at the family level of taxonomy, which will be maintained by following appropriate Standard Operating Procedures (SOPs) and QA/QC procedures (Appendix C i-ii and Appendix D i-ii).

Representativeness

Sampling methods and techniques, sample preservation, and sample handling are interactive factors that directly affect achievement of representativeness of benthic macroinvertebrate sampling. The experimental design for the biological monitoring program is described in section B of this document. Standard Operating Procedures are utilized by the regional biologists that address station selection, sampling techniques, collection, preservation, handling, and processing to maintain standards of representativeness in the surveys.

Comparability

Comparability of biomonitoring data is a summation of quality products at each phase of the data gathering process. It includes representative sampling, sample handling procedures, and procedures for reporting of biological data. Following SOPs based on published methodology, uniform sampling procedures, and semi-annual training workshops ensure that regional biologists make accurate assessments of water quality statewide.

A8 – Training Requirements/ Certification

All field sampling as well as laboratory sample processing (subsorting of benthic macroinvertebrates) will be performed by, or under the supervision of, a professional aquatic biologist.

All taxonomic identifications will be performed by an aquatic biologist that has obtained a certification from Virginia Commonwealth University or the North American Benthological Society. Certifications are earned by passing a family level taxonomic identification proficiency test established by professional benthic macroinvertebrate taxonomists.

Agencies and organizations outside of the VADEQ must submit a QAPP to the VADEQ and this QAPP must be approved by the biological monitoring program coordinator before their biological data will be used for assessment purposes. QAPP requirements for non-DEQ agencies and organizations are provided in the document "Guidelines for DEQ review and approval of biological monitoring QAPPs submitted by non-DEQ sources" (2006).

A9 – Documentation and Records

The QAPP for this project was written by VADEQ staff and will be sent to the appropriate EPA Region 3 QAPP contact for review. The most up-to date version of this QAPP will be available through the biological monitoring program coordinator and will also be available on VADEQ's website.

All field data (habitat assessments, field observations, and water physicochemical measurements) are entered on standardized forms that are completed at the time of sampling (see Appendix D i). Water physicochemical data are later entered into CEDS in the laboratory. Lists of all identified taxa, physicochemical data, and habitat scores are entered and stored by station in VA Ecological Data Application System (EDAS), an ACCESS© database that facilitates the archiving and retrieving of taxonomic information. The VA EDAS database provides information that is summarized in the Agency's biennial 305(b) Water Quality Assessment Report. Results are also submitted to EPA under VADEQ's Section 106 agreement.

Each regional biologist will keep originals of all field data sheets, taxonomic records, quality control records, instrument calibration records, and miscellaneous correspondence and notes related to the specific sampling stations in the appropriate dedicated storage locations. Final assessment reports will be sent to the appropriate VADEQ staff for each regional office.

Group B: Measurement/ Data Acquisition Elements

B1 – Sampling Process Design

The VADEQ employs two main types of sampling strategies, probabilistic monitoring and targeted monitoring. The probabilistic monitoring network is a set of randomly chosen stations used to make statistically based assessments of Virginia's streams. This approach differs from targeted monitoring by selecting stations randomly rather than with bias for access or specific data needs. Data from randomly selected stations represents an unbiased distribution of statewide conditions and allows a measure of accuracy of these data.

Targeted monitoring is based on choosing stations for specific data needs, such as reviewing VPDES permits, tracking local pollution events, and other rationale described in section A – 6 of this document.

B2 - Sampling Methods

The sampling methods for the biological monitoring program are shown in the SOPs in Appendix B (i & ii). See section A-6 (stream macroinvertebrate sampling) for sample method determination.

B3 – Sample Handling and Custody

Each regional biologist will be responsible for the appropriate preservation, labeling, transport, and storage of benthic macroinvertebrate samples. (For details, see respective SOP in Appendix B). No special custody requirements of samples are required in the current program.

B4 – Analytical Methods

The SOP for benthic macroinvertebrate sub-sampling is located in Appendix B (iv).

B5 – Quality Control

Acceptable relative percent difference values and accuracy levels for quality control procedures for field and laboratory techniques for the biological monitoring program are located in Table 1.

Table 1. Quality Control Objectives for the biological monitoring program

Comparability	Accuracy and Precision	Sorting Efficiency
The expected degree of agreement between replicate benthic macroinvertebrate samples is ≥ 70%	The expected MQO for taxonomic precision is a PTD value ≤ 10%	The expected sorting efficiency of benthic macroinvertebrate samples is ≥ 90%

Comparability- Replicate samples are taken at 10% of sampling sites. The degree of agreement is based on the percent comparability of the assessment VSCI scores between replicates. If the percent comparability is < 70%, an evaluation of the consistency of field sampling techniques may be warranted.

Accuracy and Precision- The VADEQ's Measurement Quality Objective (MQO) for taxonomic precision was suggested by the EPA to be set at a Percent Taxonomic Disagreement (PTD) value of ≤ 10%. PTD is calculated:

$$\mathrm{PTD} = \left[1 - \left(\frac{comp_{pos}}{N}\right)\right] \times 100$$

$comp_{pos}$ is the number of agreements and N is the total number of specimens in the larger of the 2 counts

PTDs are calculated for 10% of samples taken annually from each VADEQ regional biologist and other VADEQ staff certified for taxonomic identification. Samples are re-identified by an EPA approved independent taxonomist or the Biological Monitoring Coordinator. Samples that do not meet the MQO are evaluated for the types of errors involved. Counting and transcribing errors indicate that greater attention to sample processing may need to be practiced. However, consistent MQOs greater than the suggested PTD due to taxonomic mis-identification may warrant the need for increased taxonomic identification training.

Sorting Efficiency- VADEQ staff involved in laboratory sub-sampling of samples must first demonstrate the ability to remove ≥ 90% of the specimens per grid. For detailed sub-sampling procedures and QA/QC, (see Appendix B iv).

The QA/QC officer/Biological Monitoring Coordinator will be responsible for conducting annual field audits to ensure appropriate SOPs are being followed in the field and lab.

B6 – Instrument / Equipment Testing, Inspecting, and Maintenance Requirements
B7 – Instrument Calibration and Frequency

Detailed information on testing, inspection, and maintenance requirements, and on calibration procedures and frequency of all multi-probe meters for measurement of stream physicochemical parameters can be found in Section IV of the "Standard Operating Procedures Manual for the Department of Environmental Quality Office of Water Quality Monitoring and Assessment" located at www.deq.state.va.us/watermonitoring/pdf/wqmsop.pdf

B8 – Inspection/ Acceptance Requirements for Supplies and Consumables

Supplies and consumables used by the biological monitoring program are purchased through various sources. Inspections should be made before each sampling event on the D-frame dip net to ensure that there are no tears in the mesh. Sample containers should also be inspected for damage before use.

B9 –Non-direct Measurements

GIS data may be used in the determination of appropriate reference stations and to facilitate interpretation of sampling results based on watershed characteristics.

B10 – Data Management

Refer to Section A9.

Group C: Assessment/ Oversight Elements

C1 – Assessment and Response Actions

As mentioned in section A5, the VADEQ uses two bioassessment indices to assess the biotic integrity in non-tidal freshwater streams and rivers in Virginia.

For non-coastal streams, biological assessment of the benthic macroinvertebrate community is based on the Virginia Stream Condition Index (VSCI). The individual metrics, metric calculations, and assessment categories used for VSCI assessments are presented in Appendix C (i).

The CPMI is a multimetric bioassessment index which was calibrated for low gradient Coastal Plain streams which exhibit different expected benthic macroinvertebrate communities from non-coastal streams and developed by the MACS workgroup in 1997. The CPMI consists of five metrics: Taxonomic Richness, EPT Richness, % Dominant Taxon, Hilsenhoff Biotic Index, and Percent Clingers. The scores for each metric and assessment category are summarized in Appendix C (ii).

For both the VSCI and CPMI indices, a bioassessment categorized as "excellent" or "good" results in the designation of the stream reach as "fully supporting" for Aquatic Life Use Support (ALUS). A bioassessment categorized as "stressed" or "severely stressed", results in the designation of the stream reach as "impaired or threatened waters needing a TMDL" unless a documented justification for not assessing as impaired is provided. (For detailed assessment determination, see the Water Quality Assessment Guidance Manual for Y2008 located at: http://www.deq.virginia.gov/export/sites/default/waterguidance/pdf/072010.pdf).

For the CPMI, values obtained may sometimes be intermediate to established ranges and require some subjective judgment as to the assessment of biological condition. In these instances, habitat assessment and water quality data may aid in the assessment process.

Each regional biologist is required to document any problems encountered during data collection, sample processing, or data analysis, and to take remedial action where required. Such action may include resampling or eliminating data from further consideration.

C2 – Reports to Management

Biomonitoring program staff will discuss QA/QC issues at regularly scheduled meetings or as the need arises. Yearly reports will be developed by the program QA/QC officer and distributed to the regional environmental managers and biologists. A summary of

QA/QC activities , including any conditions or situations affecting data completeness or quality, corrective actions, and outcomes of corrective actions will be prepared as part of the final report.

Group D: Data Validation and Usability

D1 – Data Review, Validation, and Verification Requirements

All field and laboratory data will be reviewed, verified, and validated to ensure they conform to program specifications. It will be the responsibility of each regional biologist whether to accept or reject data.

D2 – Validation and Verification Methods

Data review, verification, and validation will be performed using self-assessment and peer and management review. Data will initially be validated by the regional biologist when returning from the field and further validated during entry into the EDAS database. Any errors detected will be rectified by editing incorrect database entries, resampling, or excluding questionable data. Biological data approved by the regional environmental managers will be given to the appropriate waterbody assessment personnel.

D3 – Reconciliation with Data Quality Objectives

All data collected by the biological monitoring program will be reviewed on an ongoing basis for accuracy, precision, and completeness. If data quality does not meet the appropriate specifications, data will be discarded and resampling may occur.

Group E: Program Assurance

E1 – Audit Verification

The Program and Performance Audits verify that procedures specified in this Project Plan are being utilized. These audits insure the integrity of the reported data. For this program, audits are divided into two major topic areas:

- Field Sampling
- Laboratory

E2 - Field Audits

The internal audits used to evaluate field sampling will examine:

- Sampling Sites
- Sample Collection Procedures
- Assessment of Site

E3 - Laboratory Audits

The internal audits used to evaluate the laboratory will examine:

- SubSampling Procedures
- QA/QC Efficiency
- Taxonomic Skill

References

Barbour, M.T., J. Gerritsen, and B.D. Snyder and J.B. Stribling. 1999. Rapid bioassessment protocols for use in streams and rivers; periphyton, benthic macroinvertebrates, and fish 2nd edition. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA841-b-99-002.

Maxted, J.R., M.T. Barbour, J. Gerritsen, V. Poretti, N. Primrose, A. Silvia, D. Penrose, and R. Renfrow. 2000. Assessment framework for mid-Atlantic coastal plain streams using benthic macroinvertebrates. J. N. Am. Benthol. Soc., 19(1):128-144.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.EPA/440/4-89/001.

Stribling, J.B., S.R. Moulton, G.T. Lester. 2003. Determining the quality of taxonomic data. J. N. Am. Benthol. Soc., 22(4):621-631.

Appendix A

List of Acronyms

AAC	Academic Advisory Committee
ALUS	Aquatic Life Use Support
CEDS	Comprehensive Environmental Data System
CO	Central Office
CPMI	Coastal Plain Macroinvertebrate Index
EDAS	Ecological Data Application System
GIS	Geographical Information Systems
MACS	Mid-Atlantic Coastal Streams
MQO	Measurement Quality Objective
NRO	Northern Regional Office
PTD	Percent Taxonomic Disagreement
PRO	Piedmont Regional Office
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RBP II	Rapid Bioassessment Protocols (II)
SCRO	South Central Regional Office
SOP/SOPs	Standard Operating Procedure(s)
SWRO	South West Regional Office
TMDL	Total Maximum Daily Load
TRO	Tidewater Regional Office
EPA	United States Environmental Protection Agency
VADEQ	Virginia Department of Environmental Quality
VPDES	Virginia Pollutant Discharge Elimination System
VRO	Valley Regional Office
VSCI	Virginia Stream Condition Index
WCRO	West Central Regional Office

Appendix B (i)

SOP Title: Methods for Benthic Macroinvertebrate Collections in Cobble Substrate (single habitat)

Date of Last Revision: 12/28/2007

Equipment/Materials:

Standard aquatic dip net
0.3 meter width (~1 foot)
Wash bucket
Sample containers
Field notebook
First aid kit
D-frame (500-µm mesh openings)
Sieve bucket (500-µm mesh openings)
70 percent isopropyl
Forceps
Pencils

References:

Barbour, M.T., J. Gerritsen, and B.D. Snyder and J.B. Stribling. 1999. Rapid bioassessment protocols for use in streams and rivers; periphyton, benthic macroinvertebrates, and fish 2nd edition. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA841-b-99-002.

Procedures:

Habitat:	Riffles, Runs
Area:	2m² total; 6 kicks of 1 meter or 12 kicks of ½ meter
Mesh Size	500-µm mesh openings
Index Period	Regional consideration or sample reference sites during same period, decisions based on project/program objectives

1. The sample reach (considered to be a station) should extend to a 100-meter instream segment of habitat having no major tributaries in the assessment area. Sampling should be conducted at least 100-meters upstream of any road or bridge crossing to minimize the affects on stream velocity, depth, and overall habitat.

2. Starting at the downstream end of the reach and moving upstream, all riffles and runs are candidates for sampling throughout the reach. Sampling is conducted holding the dipnet on the bottom of the stream and kicking the cobble substrate (i.e., riffles and runs) to agitate and dislodge organisms. A single kick consists of disturbing the substrate upstream of the net by kicking with the feet and/or by using the hands to dislodge the cobble/boulder for **30 seconds – 1 minute**. Six kicks one meter above the dipnet or 12 kicks of half a meter above dipnet should be used to sample a total of 2m², at **30 seconds – 1 minute** per kick net sample.

3. *Riffles/Runs* – Shallow part of the stream where water flows swiftly over completely or partially submerged pebble to boulder sized rocks to produce surface agitation. Sample by holding the bottom rim of the dip net against the substrate downstream of the riffle and perpendicular to the flow while disturbing the substrate just upstream of the net with feet and hands to dislodge organisms.

4. The collected sample is washed by running clean stream water through the net 2-3 times. The sample is then transferred to the sieve bucket if needed. Do not let the net become so clogged with debris that it results in the diversion of water around the net rather than through the net. If clogging occurs, discard the sample that is in the net and redo that portion of the sample in a different location.

5. As the sample is added to the sieve bucket (when needed), it should be further washed to remove fines. While sieving, remove large debris from the sample after rinsing and inspecting for organisms, and place any organisms back into the sieve bucket. Do not attempt to inspect small debris.

6. Transfer the sample from the kick net or sieve bucket to a prelabeled sample container(s) and preserve in 70 percent isopropyl alcohol. Forceps may be needed to remove organisms from the screen and dipnet.

7. Complete the Benthic Macroinvertebrate Field Data Sheet including comments on weather and wildlife observations, etc. Notes on the stable habitats sampled should be recorded. (i.e., the proportion of snags, vegetation, etc. sampled, the type of substrate, and the condition of the habitats).

Quality Control (QC)

1. Field sampling QC involves the collection of replicate samples at various reaches to verify the repeatability of the results obtained by a single set of field investigators. Each investigation team should conduct replicate sampling at 10 percent of the sampling reaches. Replicate sampling is conducted on an adjacent reach upstream of the initial sampling. The adjacent reach should be similar to the initial site in respect to habitat, stressors, point source pollution, etc. Replicate samples are preserved, subsampled, and the organisms are identified using SOPs. Results are recorded in a sampling QC log book.

2. Sample labels should include the following information: station ID, date and time, preservative, habitat sampled, and sampler's name.

Appendix B (ii).

SOP Title: Methods for Multi-habitat Benthic Macroinvertebrate Collections

Date of Last Revision: 12/28/2007

Equipment/Materials:

Standard aquatic dip net
0.3 meter width (~1 foot)
Wash bucket
Sample containers
Field notebook
First aid kit
D-frame (500-µm mesh openings)
Sieve bucket (500-µm mesh openings)
70 percent isopropyl
Forceps
Pencils

References:

United States Environmental Protection Agency. 1997. Field and laboratory methods for macroinvertebrate and habitat assessment of low-gradient nontidal streams. Mid-Atlantic Coastal Streams Workgroup, Environmental Services Division, Region 3, Wheeling, W.V

Barbour, M.T., J. Gerritsen, and B.D. Snyder and J.B. Stribling. 1999. Rapid bioassessment protocols for use in streams and rivers; periphyton, benthic macroinvertebrates, and fish 2nd edition. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA841-b-99-002.

Procedures:

Habitat:	Snags, Vegetation, Banks, Riffles
Area:	20 jabs, each 1-m in length
Mesh size:	500-µm mesh openings
Index Period	Regional consideration or sample reference sites during same Period decisions based on project/program objectives

1. The sample reach (considered to be a station) should extend to a 100-meter instream segment of habitat having no major tributaries in the assessment area. Sampling should be conducted at least 100-meters upstream of any road or bridge crossing to minimize the affects on stream velocity, depth and overall habitat.

2. Sampling is conducted from downstream to upstream by jabbing the D-frame net into productive and stable habitats 20 times. A single jab consists of forcefully thrusting the net into a productive habitat for a linear distance of 1-meter, followed by 2-3 sweeps of the same area to collect dislodged organisms for **30 seconds – 1 minute /jab**.

3. Different types of habitat should be sampled in rough proportion to their frequency within the reach. Unique habitat types (i.e., those consisting of less than 5 percent of stable habitat within the sampling reach) should not be sampled.

4. Identify proportional representation of habitat types. Characterize the bottom and shore-zones according to features present at the time the sample is collected. Do not base characterizations on anticipated oscillations of flow regime or substrate compositions.

a) Bottom-zone (within channel substrate)
    - Riffles have relatively fast velocity, shallow steam depth, steep surface gradient, and a straight to convex channel profile. Riffles are usually topographic high areas produced by the accumulation of coarse materials.
    - Non-riffle encompasses all other forms (i.e., pools, runs, and slack areas) and generally possesses intermediate to fine particle substrate.
    - Vegetation, such as submerged macrophytes, serve as habitat for macroinvertebrates and may constitute large areas of the available substrate.

b) Shore-zone (allochthonous material)
    - Overhanging vegetation includes terrestrial shore-zone plant material that is living, submerged, and provides in-stream cover for fish and macroinvertebrates.
    - Submerged tree roots include living root material from shoreline or overhanging vegetation that is submerged and provides in-stream cover for fish and macroinvertebrates.
    - Woody debris includes submerged snags and/or other woody material that has been microbially conditioned. Woody debris in the channel is considered part of the shoreline for estimating allocation of sampling.

5. Proportionally allocate sampling effort (20 jabs/sweeps/kicks) to shore-zone and bottom-zone, **30 seconds – 1 minute/jab, sweep, or kick**.

6. The collected sample is washed by running clean stream water through the net 2-3 times The sample is then transferred to the sieve bucket (if needed). Samples should be cleaned and transferred to the sieve bucket at least every five jabs, more often if necessary. Do not let the net become so clogged with debris that it results in the diversion of water around the net rather than through the net. If clogging occurs, discard the sample that is in the net and redo that portion of the sample in a different location.

7. As the sample is added to the sieve bucket (when needed), it should be further washed to remove fines. While sieving, remove large debris from the sample after rinsing and inspecting of organisms, and place any organisms back into the sieve bucket. Do not attempt to inspect small debris.

8. Transfer the sample from the kick net or sieve bucket to a pre-labeled sample container(s) and preserve in 70 percent isopropyl alcohol. Forceps may be needed to remove organisms from the sieve screen and dipnet.

Following are specific sampling techniques for different productive and stable habitats:

Riffles/Runs – Shallow part of the stream where water flows swiftly over completely or partially submerged pebble to boulder sized rocks to produce surface agitation. Sample by holding the bottom rim of the dip net against the

substrate downstream of the riffle and perpendicular to the flow while disturbing the substrate just upstream of the net with feet and hands to dislodge organisms.

Snags- Submerged woody debris, sampled by jabbing in medium-sized snag material (sticks and branches). The 1-meter section of this habitat is estimated. The snag habitat may be kicked first to help dislodge organisms, but do so only after placing net in water downstream of the snag. Accumulated woody material in pool areas can also be considered as snag habitat.

Vegetation – Aquatic plants that are rooted on the bottom of the stream. They are sampled in deep water by drawing the net through the vegetation from the bottom to the surface of the water. In shallow water, they are sampled by bumping the net along the bottom in the rooted area.

Banks – When banks have roots, plants, and snags associated with them, they are sampled in a fashion similar to snags. When the banks are of unvegetated or soft soil, they are sampled by bumping the net along the substrate rather than dragging the net through soft substrates. This will reduce the amount of detritus (defined as sticks, leaves, and/or pieces of bark) through which you would have to pick. Also, the bank habitat can be kicked first in order to help dislodge organisms.

9. Complete the Benthic Macroinvertebrate Field Data Sheet including comments on weather and wildlife observations etc. Notes on the stable habitats sampled should be recorded. (i.e., the proportion of snags, vegetation, etc. sampled, the type of substrate, and the condition of the habitats). Also note how the sample was collected; if wading in-stream, walking on the banks, out of the channel, from a boat, etc.

Quality Control (QC)

1. Field sampling QC involves the collection of replicate samples at various reaches to verify the repeatability of the results obtained by a single set of field investigators. Each investigation team should conduct replicate sampling at 10 percent of the sampling reaches. Replicate sampling is conducted on an adjacent reach upstream of the initial sampling. The adjacent reach should be similar to the initial site in respect to habitat, stressors, point source pollution, etc. Replicate samples are preserved, sub-sampled, and the organisms are identified using SOPs. Results are recorded in a sampling QC log book.

2. Sample labels should include the following information; station ID, date and time, preservative, habitat sampled, and sampler's name.

Appendix B (iii)

SOP Title: Methods for Habitat Assessment for Streams

Date of Last Revision: 12/28/2007

Equipment/Materials:
Habitat Assessment Field Sheets for (1) High Gradient Streams
(2) Low Gradient Streams
Pencils
Field notebook

References:
Barbour, M.T., J. Gerritsen, and B.D. Snyder and J.B. Stribling. 1999. Rapid bioassessment protocols for use in streams and rivers; periphyton, benthic macroinvertebrates, and fish 2nd edition. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA841-b-99-002.

Procedures:

1. Select the reaches for conducting the habitat assessment and complete the sections on general characteristics and land use.

2. The habitat assessment will be focused on evaluating the physical habitat structure of a 100-meter section of the stream and upper reaches in the catchment for the large-scale parameters.

    a) Identify the downstream point of the reach that was sampled for macroinvertebrates. Measure a 100-meter section, upstream, that is consistent with the biological sampling reach to assess large-scale parameters.

    b) Complete the identifying information on the field data sheets for the habitat assessment.

Physical Habitat Structure:

Conduct the habitat assessment. Refer to the descriptors described here and the decision criteria on the habitat assessment field data sheet.

<u>High Gradient Streams</u>

The first 5 parameters are assessed directly in the entire 100-meter reach that was used for the macroinvertebrate sampling.

1. **Epifaunal substrate/available cover** includes the relative quantity and variety of natural structures in the stream, such as fallen trees, logs and branches, cobble and large rocks, and undercut banks that are available to fish and macroinvertebrates for refugia, spawning/nursery activities, and/or feeding. A wide variety of submerged structures in

the stream provide aquatic organisms with many living spaces; the more living spaces in a stream, the more types of organisms the stream can support.

2. **Embeddedness** refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered, or sunken into the silt, sand, or mud of the stream bottom. Generally, as rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning, and egg incubation. This parameter is assessed primarily in the riffles, if present. To estimate the percent of embeddedness, observe the amount of silt or finer sediments surrounding the rocks. If kicking does not dislodge the rocks or cobbles, they may be greatly embedded. It may be useful to lift a few rocks and observe how much of the rock (e.g., ½, ⅓) is darker due to anoxic reaction on the inorganic surface.

3. **Velocity/Depth regime** is important to the maintenance of healthy aquatic communities. Fast water increases the amount of dissolved oxygen in the water, keeps pools from being filled with sediment, and helps food items like leaves, twigs, and algae move more quickly through the aquatic system. Slow water provides spawning areas for fish and shelters macroinvertebrates that might be washed downstream in higher stream velocities. Similarly, shallow water tends to be more easily aerated (i.e., hold more oxygen), but deeper water stays cooler longer. Thus, the best stream habitat will include all of the following velocity/depth combinations and can maintain a wide variety of organisms.

    a) Slow (<0.3 m/sec), Shallow (<0.5 m)
    b) Fast (>0.3 m/sec), Deep (>0.5 m)
    c) Fast, Shallow
    d) Slow, Deep

4. **Sediment deposition** is a measure of the amount of sediment that has been deposited in the stream channel and of the changes to the stream bottom that have occurred as a result of the deposition. Excessive levels of sediment deposition create an unstable and continually changing environment that is unsuitable for many aquatic organisms. Sediments are naturally deposited in areas where flow is obstructed. These deposits can lead to the formation of islands, shoals, or point bars (sediment that builds up in the stream, usually at the beginning of a meander) and can result in the complete filling in of pools. To determine whether or not these sediment deposits are new, look for vegetation growing on them: new sediments will not yet have been colonized by vegetation.

5. **Channel flow status** determines the percentage of the channel that is filled with water. The flow status will change as the channel enlarges or as flow decreases as a result of dams and other obstructions, diversions for irrigation, or drought. When water does not cover much of the streambed, less living area is available for aquatic organisms. Assess the wetted width of the stream in relation to the location of the lower bank.

The next 2 parameters should be assessed along a length of stream that includes the sampling reach plus 1 or 2 reaches upstream.

Channel alteration is basically a measure of large-scale changes in the shape of the stream channel. Many streams in urban and agricultural areas have been straightened, deepened (e.g. dredged), or diverted into concrete channels, often for flood control purposes. Such streams have far fewer natural habitats for fish, macroinvertebrates, and plants than do naturally meandering streams. Channel alteration is present when the stream runs through a concrete channel; when artificial embankments, riprap, and other forms of artificial bank stabilization or structures are present; when combined sewer overflow (CSO) pipes are present; when the stream is of uniform depth due to dredging; and when other such changes have occurred. Signs that indicate the occurrence of dredging include straightened, deepened, and otherwise uniform stream channels, and the removal of streamside vegetation to provide dredging equipment access to the stream.

6. **Frequency of riffles (or bends)** is a way to measure the heterogeneity occurring in a stream. Because riffles are a good source of high-quality habitat and faunal diversity, an increase in the frequency of riffles provides for greater diversity of the stream community. In streams where riffles are uncommon, a measure of the frequency of bends can be used as a measure of meandering or sinuosity, which also provides for a diverse habitat and fauna. Additionally, streams with a high degree of sinuosity are better suited to handle storm surges through absorption of energy by bends as well as providing refugia for fauna during storm events.

For the last 3 parameters, visually evaluate the condition of the right and left stream banks, separately. Face downstream to determine left from right. Assess these parameters along the stream margins for the sampling reach as well as 1 or 2 adjacent reaches, up or down stream, also facing downstream.

7. **Bank stability** measures erosion potential and whether or not the stream banks are eroded. Steep banks are more likely to collapse and suffer from erosion than are gently sloping banks and are, therefore, considered to have high erosion potential. Signs of erosion include crumbling; unvegetated banks, exposed tree roots, and exposed soil.

8. **Bank vegetative protection** measures the amount of the stream bank that is covered by natural (i.e., growing wild and not obviously planted) vegetation. The root systems of plants growing on stream banks help hold soil in place, reducing erosion. Vegetation on banks provides shade for fish and macroinvertebrates and serves as a food source by dropping leaves and other organic matter into the stream. Ideally, a variety of vegetation should be present, including trees, shrubs, and grasses. Vegetative disruption may occur when the grasses and plants on the streambanks are mowed or grazed upon, or the trees and shrubs are cut back or cleared.

9. **Riparian vegetative zone width** is defined here as the width of natural vegetation from the edge of the stream bank. The riparian vegetative zone is a buffer zone to pollutants entering a stream from runoff. It also controls erosion and provides stream habitat and nutrient input into the stream. A wide, relatively undisturbed riparian vegetative zone reflects a healthy stream system. Narrow, far less useful riparian zones occur when roads, parking lots, fields, lawns and other artificially cultivated areas, bare soil, rocks, or buildings are near the stream bank. The presence of "old fields" (i.e., previously developed agricultural fields allowed to convert to natural conditions) should rate higher than fields in continuous or periodic use.

Low Gradient Streams

10. **Epifaunal substrate/available cover** includes the relative quantity and variety of natural structures in the stream, such as fallen trees, logs and branches, cobble and large rocks, and undercut banks, that are available to fish and macroinvertebrates for refugia, spawning/nursery activities, and/or feeding. A wide variety of submerged structures in the stream provide aquatic organisms with many living spaces. The more living spaces in a stream, the more types of organisms the stream can support.

11. **Pool substrate characterization** refers to the type and condition of bottom substrates found in pool sediment types (e.g., gravel, sand) and rooted aquatic plants that support a wider array of organisms than pools dominated by mud or bedrock and with little or no plants. Additionally, streams with a variety of substrate types will support far more types of organisms than streams with uniform pool substrates.

12. **Pool variability** rates the overall mixture of pool types found in streams according to size and depth. Streams with many pool types support a wider variety of organisms than streams with fewer pool types. Thus, the best stream habitat will include all of the following pool types and can maintain a wider variety of aquatic species.

    a) Large (>half cross-section of stream), Shallow (<1.0 m)
    b) Small (<half cross-section of stream), Deep (>1.0 m)
    c) Large, Deep
    d) Small, Shallow

13. **Sediment deposition** is a measure of the amount of sediment that has been deposited in the stream channel and of the changes to the stream bottom that have occurred as a result of the deposition. Excessive levels of sediment deposition create an unstable and continually changing environment that is unsuitable for many aquatic organisms. Sediments are naturally deposited in areas where the stream flow is reduced, such as pools and bends, or where flow is obstructed. These deposits can lead to the formation of islands, shoals, or point bars (sediments that build up in the stream, usually at the beginning of a meander) or can result in the complete filling in of pools. To determine whether or not these sediment deposits are new, look for vegetation growing on them: new sediments will not yet have been colonized by vegetation.

14. **Channel flow status** determines the percent of the channel that is filled with water. The flow status will change as the channel enlarges or as flow decreases as a result of dams and other obstructions, diversions for irrigation, or drought. When water does not cover much of the streambed, less living area is available for aquatic organisms. Assess the wetted width of the stream in relation to the location of the lower bank.

The next 2 parameters should be assessed along a length of stream that includes the sampling reach plus one or two reaches upstream.

15. **Channel alteration** is basically a measure of large-scale changes in the shape of the stream channel. Many streams in urban and agricultural areas have been straightened, deepened (e.g., dredged), or diverted into concrete channels, often for flood control

purposes. Such streams have far fewer natural habitats for fish, macroinvertebrates, and plants than do naturally meandering streams. Channel alteration is present when the stream runs through a concrete channel; when artificial embankments, riprap, and other forms of artificial bank stabilization or structures are present; when the stream is very straight for significant distances; when dams, bridges, and flow-altering structures, such as combined sewer overflow (CSO) pipes are present; when the stream is of uniform depth due to dredging; and when other such changes have occurred. Signs that indicate the occurrence of dredging include straightened, deepened, and otherwise uniform stream channels, and the removal of streamside vegetation to provide dredging equipment access to the stream.

16. **Channel sinuosity** is a way to measure the meandering or sinuosity occurring in a stream. A stream with a high degree of sinuosity provides for a more diverse habitat and fauna than a stream with a low degree of sinuosity. Additionally; streams with a high degree of sinuosity are better suited to handle storm surges through absorption of energy by bends as well as providing refugia for fauna during storm events.

For the last 3 parameters, visually evaluate the condition of the right and left stream banks, separately. Face downstream to determine left from right. Assess these parameters along the stream margins for the sampling reach as well as 1 or 2 adjacent reaches.

17. **Bank stability** measures erosion potential and whether or not the stream banks are eroded. Steep banks are more likely to collapse and suffer from erosion than are gently sloping banks and are therefore considered to have a high erosion potential. Signs of erosion include crumbling, unvegetated banks, exposed tree roots, and exposed soil.

18. **Bank vegetative protection** measures the amount of the stream bank that is covered by natural vegetation (i.e., growing on stream banks) which helps hold soil in place, reducing erosion. Vegetation on banks provides shade for fish and macroinvertebrates and serves as a food source by dropping leaves and other organic matter into the stream. Ideally, a variety of vegetation should be present, including trees, shrubs, and grasses. Vegetative disruption may occur when the grasses and plants on the streambanks are mowed or grazed upon, or the trees and shrubs are cut back or cleared.

19. **Riparian vegetative zone width** is defined here as the width of natural vegetation from the edge of the stream bank. The riparian vegetative zone is a buffer zone to pollutants entering a stream from runoff. It also controls erosion and provides stream habitat and nutrient input into the stream. A wide, relatively undisturbed riparian vegetative zone reflects a healthy stream system. Narrow, far les useful riparian zones occur when roads, parking lots, fields, lawns and other artificially cultivated areas, bare soil, rocks, or buildings are near the stream bank. The presence of "old fields" (i.e., previously developed agricultural fields allowed to convert to natural conditions) should rate higher than fields in continuous or periodic use.

To perform the habitat assessment data analysis, rate each of the above 10 parameters for either high or low gradient streams and combine the ratings into a single index score.

20. Perform habitat assessment data analysis. To properly evaluate the condition of the stream site, compare it to an optimal or best condition found in the region (reference

condition). In an ideal world, the reference condition would reflect the water quality, habitat, and aquatic life characteristics of pristine sites in the same ecological region as your stream. In real life, however, few pristine sites remain. The reference condition is, therefore, generally a composite of sites that reflect the best physical, chemical, and biological conditions existing in the ecological region. To make this comparison to reference conditions, divide the index score for your stream site by the score for the reference conditions and multiply by 100 to obtain a percent similarity. Compare the results to the table below to obtain the habitat quality category for your site.

Reference Scores for Sampling Site Comparison		
Percent Similarly to Reference Score[a]	Habitat Quality Category	Attributes
≥90%	Excellent	Comparable to the best situation to be expected within an ecoregion. Excellent overall habitat structure conducive to supporting healthy biological community.
75-88%	Good	Habitat structure slightly impaired. Generally, diverse instream habitat well –developed; some degradation of riparian zone and banks; a small amount of channel alteration may be present.
60 – 73%	Fair	Loss of habitat compared to reference. Habitat is a major limiting factor to supporting a healthy biological community
≤ 58%	Poor	Severe habitat alteration at all levels.

[a]If your score falls at or near the break between habitat quality categories, use your BPJ to determine the appropriate rating.

21. Perform QC on the datasheets. Habitat assessment sheets and any field data sheets

Percent Similarly to Reference Score[a]	Habitat Quality Category	Attributes

Habitat assessments are subjective evaluations and are potentially subject to variability among investigators. Minimize variability by proper training, discuss habitat parameters, and conduct evaluations as a team. See Barbour et al. (1999) for more specific guidance.

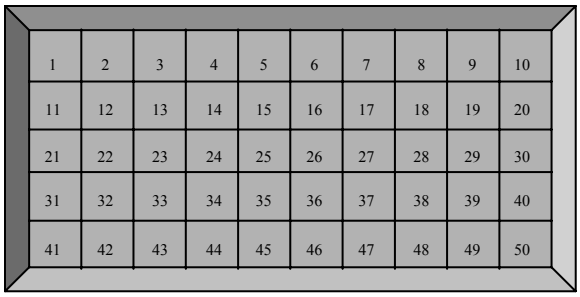
Appendix B (iv)

Title: Methods for Laboratory Sorting and Subsampling of Benthic Macroinvertebrate Samples

Date of Last Revision: 12/28/2007

Equipment/Materials:

Forceps
Standardized gridded tray (500 µm screen, 50 quadrants, each 25 cm^2)
Scissors
Small putty knife
Quadrant-sized square metal "cookie cutter"
White plastic or enamel pan for sorting
70% isopropyl alcohol
Specimen vials, caps, or stoppers
Sample labels
Dissecting microscope for organism identification (10-40x)
Macroinvertebrate Log Book
Benthic Macroinvertebrate Subsampling bench sheet



Subsampling Tray

References:

Caton, L. W. 1991. Improved sub-sampling methods for the EPA "Rapid Bioassessment" Benthic protocols. Bulletin for the North American Benthological Society 8(3):317-319.

Barbour, M.T., J. Gerritsen, and B.D. Snyder, and J.B. Stribling. 1999. Rapid bioassessment protocols for use in streams and rivers: periphyton, benthic macroinvertebrates, and fish, 2nd Edition. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA841-B-00-002.

General:

The sorting and subsampling of the macroinvertebrate samples in the laboratory facilities include processing and identification of organisms collected in wadeable streams. A randomized 110-organism sub-sample is sorted and preserved using a special Caton gridded tray and screen, designed by Larry Caton, Oregon Department of Environmental Quality (Caton, 1991). Documentation for the level of effort, or proportion of sample processed, is recorded on the Benthic Macroinvertebrate Laboratory Bench Sheet.

Internal Label Information Required for each Vial of Sorted Material and Vial of Identified Macroinvertebrates:

- Station Name
- Station Location
- Station ID
- Sampling Date and Time
- Sorter's Initials
- "1 of 2" "2 of 2" if necessary

Procedures:

1. Log each sample (as it is received) on the Benthic Sample Log-in sheet (located in the Benthic Log Book) until ready for processing.

2. Remove the lid from the sample container or open the sample and pull out the internal sample label (save the sample label – it will need to be transferred into the sample vial of macroinvertebrates). Record sample collection information on the Benthic Macroinvertebrate Laboratory Bench Sheet. Header information required includes: station ID, station location, station number, sample type, date the sample was collected, the field team who collected the sample, person subsorting, # of grids subsorted, person identifying the insects, total # of subsorted insects, and sorting date.

3. Transfer the homogenized sample material to the gridded Caton tray (use more than one sub-sampling device if necessary). Wash the sample thoroughly by running tap water over it to remove any fine material.

4. Place the gridded tray into a larger tray or sink. Add enough water to spread the sample evenly throughout the Caton grid (the water level should be relatively close to the top of the tray). Spread the sample material over the bottom of the pan as evenly as possible. Move the sample into the corners of the pan using forceps, a spoon, or by hand. Vibrate or shake the pan gently to help spread the sample.

5. Lift the screen out of the larger tray or sink to drain.

6. Use a random number generator to select a grid to process. Remove all the material from that grid and place the removed material into a separate holding container, such as a white, plastic or enamel pan. The material is removed as follows:

    a. Place the metal dividing frame or "cookie cutter" over the sample at the approximate location of the grid selected for processing (based on the numbers marked on the sides of the gridded tray). Use a pair of rulers or other straight edges to facilitate lining up the cookie cutter at the intersection, if necessary.

    b. Remove the material within the "cookie cutter" using a putty knife, a teaspoon, or forceps. Depending on the consistency of what is in the sample,

it might be necessary to cut the material along the outside of the "cookie cutter" with scissors or putty knife so that only one grid's worth of sample material is used. Inspect the screen for any remaining organisms. Use the following rules when dealing with organisms that lie on the line between two grids:

- An organism belongs to the grid containing its head.

- If it is not possible to determine the location of the head (i.e., for worms), the organism is considered to be in the grid containing most of its body.

- If the head of an organism lies on the line between two grids, all organisms on the top of a grid and those on the right side of a grid belong in that grid and are picked with that grid

c. Place the material from the selected grid(s) into a separate white plastic or enamel pan. Add the necessary amount of water to the pan to facilitate sorting.

7. Completely remove all macroinvertebrates from the selected (**First**) grid by transferring a spoonful of the material to a Petri dish for examination beneath a dissecting microscope or place the selected grid in a tray and place under a magnifying glass to remove organisms (**all organisms should NOT be removed with the naked eye only**) and store organisms in an internally-labeled vial (or larger container, if necessary) containing 70% isopropyl alcohol as a preservative. If more than 30 organisms are selected from the first grid, use your **best professional judgment**, with regards to whether or not you should subsample. If subsampling skip to step 8, if not continue with step 7a;

   a. Keep a count of the number of organisms removed and enter the number of organisms found in each grid under the correct column on the Sub-Sample and Sample Reduction Sheet (Appendix D ii).

   b. Continue selecting and processing randomly selected quadrates until 110 organisms are counted. **Each grid begun must be picked to completion; that is, even if the target is reached halfway through a grid, finish the entire grid. A minimum of 4 grids must be picked.** Record the number of quadrates in the subsample on the Benthic Macroinvertebrate Laboratory Bench Sheet (use multipliers from the table for high density samples).

   c. Do not remove or count empty snail or bivalve shells, pupae, or incidentally-collected terrestrial taxa. Also do not count fragments, such as legs, antennae, gills, or wings. For Oligochaeta, attempt to remove and count only whole organisms and fragments that include the head. Do not count fragments that do not include the head.

d. If the last grid being processed results in more than 121 organisms (i.e., 10% above target number), evenly redistribute all of the organisms (without detritus) in a 15 grid dish or tray containing water to cover the sample. Use a random numbers table and counting backwards, from your total count, remove organisms from selected grid (s) (remember to remove ALL organisms in selected grid) until you are left with your target count of 110 organisms within 10% (99-121) remaining in the tray. The organisms that are removed may be discarded and the organisms that are remaining in your tray are your benthic sample to be identified.

e. Identify all the organisms in the sample to family **(retain identified sample in vial for three years)**, record the number of organisms from each family on the Benthic Macroinvertebrate Bench Sheet, and enter the data into EDAS.

8. Processing of high density samples

a. Discard all of the organisms picked from the first grid.

b. Using a random numbers table, take the number of grids designated by the table below **all at once, these removed grids will d**epend upon the number of organisms found in the first grid. The removed grids will now be your sample to re-subsample. An **example** of removal would be the following; when removing 15, 20, or 25 grids you should be able to remove 3, 4, or 5 columns from the box. For example if you are to remove 15 grids, choose 3 random numbers (ie. 3, 28, 55) and remove **columns** 3, 8, and 5. If you are to remove 10 grids, choose 5 numbers (ie. 2, 45, 77, 66, and 91) and remove grids next to one another. For example, grids 2 and 3 as well as 5 and 6 that are located in column 4, and grids 7 and 8 that are located in column 7, etc…. Place the selected removed grids in the sorting tray and set aside. Discard the remaining sample in the subsampling box.

c. Completely mix the selected grids in the tray. If the first grid has more than 30 organisms, use your ***best professional judgment***, with regards to whether or not you should re-subsample, and then go back to step 7 a-f.

Organisms per grid in original sample	Remove and keep following number of grids	Predicted number of organisms per grid	Predicted number of grids to reach 110	Multiplier for recording total number of grids picked
30-45	25	15 - 25.5	5 – 7	0.5
46-55	20	18.4 - 22	5 – 6	0.4
56-75	15	16.8 – 22.5	7 – 5	0.3
76-110	10	15.2 - 22	5 – 7	0.2
111-230	5	11.1 - 22	5 – 10	0.1
231-315	4	18.48 – 25.2	6 – 4	0.08

*4 quadrates must be removed. If removal leads to over 121 organisms, subsampling will continue as described in step 6d.

Documentation:

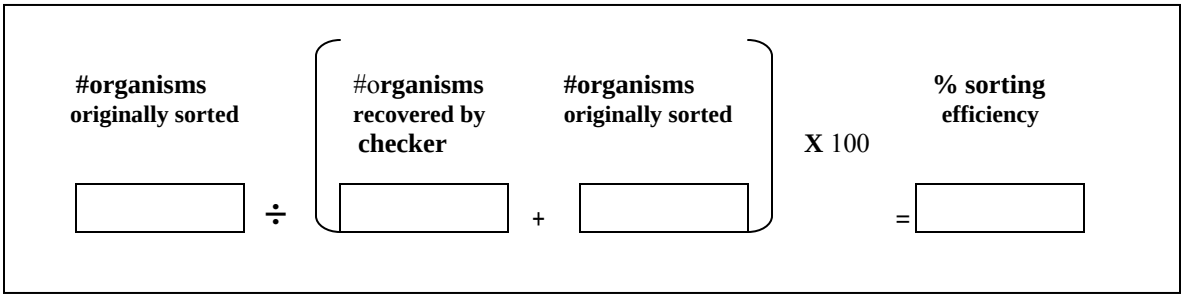
1. Complete a Benthic Macroinvertebrate Laboratory Bench Sheet for each sample as it is processed.

QA/QC

Because it can be difficult to detect the organisms in stream samples (due to inexperience, detritus, etc.), only persons who have received instruction by senior biology staff familiar with processing benthic samples can perform a quality control (QC) check. These QC checks must be performed immediately following sorting of each grid. Therefore, a regional biologist must perform QC checks anytime samples are processed by an inexperienced individual and each person deemed "experienced" will be checked **once per year** by another experienced sorter.

1. Initially, experienced personnel will check all sorted quadrates from the first three samples processed by a sorter to ensure that all organisms were removed from the detritus. This will not only apply to inexperienced sorters, but also to those deemed "experienced." Qualification will only occur when sorters are consistent in achieving ≥ 90% sorting efficiency after at least three samples have been checked.

2. The QC checker will calculate sorting efficiency for each sample (number of organisms/sample found by the initial sorter ÷ total number of organisms/sample found by QC Officers × 100 = %), If sorting efficiency for each of these three consecutive samples is ≥ 90% for a particular individual, this individual is considered "experienced" and can serve as a QC checker. In the event that an individual fails to achieve ≥ 90% sorting efficiency, they will be required to sort an additional three samples in order to continue to monitor their sorting efficiency. However, if they show marked improvement in their sorting efficiency prior to completion of the next three samples, whereby they acquire the ≥ 90% sorting efficiency, the QC checker may, at his/her discretion, consider this individual to be "experienced." Sorting efficiency should not be calculated for samples processed by more than one individual.


#organisms
originally sorted
÷
#organisms
recovered by
checker
+
#organisms
originally sorted
X 100
% sorting
efficiency
=

Appendix C (i)

Virginia Stream Condition Index (VSCI): Metric scoring criteria, assessment catergories, and metric definitions

Metrics
1. Total Taxa (a)
2. EPT Taxa (a)
3. % Ephemeroptera (a)
4. % Plecoptera + Trichoptera less Hydropsychidae (a)
5. % Scrapers (a)
6. % Chironomidae (b)
7. % Top 2 Dominant (b)
8. HBI (family) (c)

a. Score is the total possible score * the (metric value / by the standard best value X_{95}).

b. Score is the total possible score * the (total possible score - the metric value/the total possible score - the standard best value X_5).

c. Score is the total possible score * the (total possible score - the metric value/the total possible score - the standard best value X_5).

Total Possible Score = 100

Assessment Category	Score Range
Excellent	≥73
Good	60-72
Stress	59-43
Severe Stress	≤42

Metric	Definition	Responses to Increased pertubation
1. Total Taxa	Measures total number of taxa observed.	Decrease
2. EPT Taxa	Measures total number of pollution sensitive Ephemeroptera, Plecoptera, and Trichoptera observed.	Decrease
3. % Ephemeroptera	Measures % Ephemeroptera taxa present in sample.	Decrease
4. % Plecoptera + Trichoptera less Hydropsychidae	Measures % Plecoptera + Trichoptera, subtracting pollution tolerant Hydropsychidae	Decrease
5. % Scrapers	Measures % scraper functional feeding group present in sample.	Decrease
6. % Chironomidae	Measures % pollution tolerant Chironomidae present in sample.	Increase
7. % Top 2 Dominant Taxa	Measures % dominance of the 2 most abundant taxa.	Increase
8. HBI (family)	Hilsenhoff Biotic Index.	Increase

Appendix C (ii)

The Coastal Plain Macroinvertebrate Index (CPMI): Metric scoring criteria, assessment categories, and metric definitions

	Metric Scoring Criteria			
Metric	6	4	2	0
1. Total Taxa	>17	12-17	6-11	<6
2. EPT Taxa	>6	5-6	3-4	<3
3. % Ephemeroptera	>24%	16-24%	8-15%	<8%
4. HBI	<5.7	5.7-6.4	6.5-7.2	>7.2
5. % Clingers	>26%	18-26%	9-17%	<9%

Total Possible Score = 30

Assessment Category	Score Range
Excellent	24 - 30
Good	16 - 22
Stress	6 - 14
Severe Stress	0 - 4

Metric	Definition	Response to increased pertubation
Total Taxa	Measures the overall variety of the macroinvertebrate assemblage	Decrease
EPT Taxa	Number of taxa in the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Tricoptera (caddisflies)	Decrease
% Ephemeroptera	Percent of mayfly nymphs	Decrease
Hilsenoff Biotic Index (HBI)	Uses tolerance values to weight abundance in an estimate of overall pollution	Increase
% Clingers	Percent of insects having fixed retreats or adaptations for attachment to surfaces in flowing water	Decrease

Appendix D (i)

Benthic Macroinvertebrate Field Data Sheet (front)

Station ID:		Ecoregion	
Field Team:		Survey Reason:	
Stream Name:		Land Use:	
Location:			
DATE		Start Time	Finish Time
LATITUDE (Decimal degrees)		LONGITUDE (Decimal degrees)	GPS Signal

Stream Physicochemical Measurements

Instrument ID number:_____ pH: _____

TEMPERATURE:_____ºC CONDUCTIVITY:_____µS/cm

DISSOLVED OXYGEN:_____mg/L Did instrument pass all post-calibration checks? Y / N

(If NO- which parameter(s) failed and action taken: _____

Benthic Macroinvertebrate Collection

Method used (circle one) **Single Habitat** (Riffle) **Multi Habitat** (Logs, plants, etc.)

Riffle quality (circle one) **Good** **Marginal** **Poor** **None**

Habitats sampled (circle one) **Riffle** **Snags** **Banks** **Vegetation**

jabs ____ ____ ____ _____

Perservative:_____ Area Sampled (square meters) :_____

Weather observations

Current weather (circle one) Cloudy Clear Rain/Snow Foggy

Recent precipitation (circle one) Clear Showers Rain Storms Other

Stream flow (circle one) Low Normal Above Normal Flood

Biological Observations

circle one in each category

0 1 2 3	Periphyton	**0 1 2 3**	Salamanders	0 = Absent
0 1 2 3	Filamentous algae	**0 1 2 3**	Warmwater Fish	1 = Sparse
0 1 2 3	Submerged Macrophytes	**0 1 2 3**	Coldwater Fish	2 = Common to Abundant
0 1 2 3	Emergent Macrophytes	**0 1 2 3**	Beavers	3 = Dominant - abnormally high
0 1 2 3	Crayfish	**0 1 2 3**	Muskrats	density where other taxa are
0 1 2 3	Corbicula	**0 1 2 3**	Ducks/Geese	insignificant in relation to the
0 1 2 3	Unionidae	**0 1 2 3**	Other…	dominant taxa.There can be
0 1 2 3	Operculate Snails	**0 1 2 3**		situations where multiple taxa
0 1 2 3	Non-operculate Snails	**0 1 2 3**		are dominant such as algae
0 1 2 3	Frogs/ Tadpoles	**0 1 2 3**		and snails.

Notes:

USE BACK OF SHEET FOR HABITAT DATA ASSESSMENT SHEET (HIGH or LOW)

Habitat Assessment Data Sheet – High Gradient (BACK)

Sample Identification

Stream Name: _____	**Location:** _____	**River Mile:** _____
Date: ___/___/___	**Time:** ___:___	**Observer:** _____

Habitat Assessment

	Optimal	Suboptimal	Marginal	Poor
1. Epifaunal Substrate / Available Cover	>70% favorable for colonization	40 – 70% stable habitat	20 – 40% stable habitat	<20% stable habitat
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
2. Embeddedness	<25% embedded	25 – 50% embedded	50 – 75% embedded	>75% embedded
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
3. Velocity / Depth Regime	All four present	3 of 4 present (score lower if missing fast-shallow)	2 of 4 present (score lower if missing fast or slow-shallow)	Only 1 velocity depth regime present
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
4. Sediment Deposition	<5% of bottom affected	5 – 30% of bottom affected; some new bar formation	30 – 50% of bottom affected; moderate deposition in slow areas	>50% of bottom affected; heavy deposits of fine sediments; pools almost absent
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
5. Channel Flow Status	Water up to lower banks	>75% of channel filled	25 – 75% of channel filled	Very little running water
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
6. Channel Alteration	Stream with natural pattern	Minimal disruption to channel (bridges or minor work)	Channelization affecting 40 – 80% of reach	Stream channelized for over 80% of reach
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
7. Frequency of Riffles (or bends)	Ratio of distance between riffle to width of stream <7:1	Ratio between 7:1 and 15:1	Ratio between 15:1 and 25:1	Ratio >25:1
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
8. Bank Stability	<5% of bank eroded or collapsed	5 – 30% of bank with evidence of erosion	30 – 60% of bank eroding	60 – 100% of bank scarred; many active areas of erosion
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
9. Vegetative Protection	>90% of bank covered by undisturbed vegetation	70 – 90% of bank covered	50 –70% of bank covered	<50% of bank covered; disruption evident
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
10. Riparian Vegetative Zone Width	>18 meters	12 – 18 meters	6 – 12 meters	<6 meters
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

Habitat Assessment Data Sheet – Low Gradient (BACK)

Sample Identification

Stream Name: _____	**Location:** _____	**River Mile:** _____
Date: ___/___/___	**Time:** ___:___	**Observer:** _____

Habitat Assessment

	Optimal	Suboptimal	Marginal	Poor
1. Epifaunal Substrate / Available Cover	>50% favorable for colonization	30-50% stable habitat	10-30% stable habitat	<10% stable habitat
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
2. Pool Substrate Characterization	Mixture of materials with gravel and sand prevalent; root mats & SAV common	Mix of soft sand, mud or clay; some root mats & SAV present	All mud, clay or sand; little / no root mat; no SAV	Hard-pan clay or bedrock; no root mat or vegetation
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
3. Pool Variability	Even mix of large-shallow, large-deep, small-shallow, small-deep pools	Majority of pools large-deep; very few shallow	Shallow pools much more common than deep	Majority small-shallow pools or pools absent
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
4. Sediment Deposition	<20% of bottom affected	20-50% of bottom affected; some new bar formation	50-80% of bottom affected; moderate deposition in pools	>80% of bottom affected; heavy deposits of fine sediments; pools almost absent
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
5. Channel Flow Status	Water up to lower banks	>75% of channel filled	25 – 75% of channel filled	Very little running water
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
6. Channel Alteration	Stream with natural pattern	Minimal disruption to channel (bridges or minor work)	Channelization affecting 40 – 80% of reach	Stream channelized for over 80% of reach
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
7. Channel sinuosity	Bends increase stream length 3 to 4 times	Bends increase stream length 2 to 3 times	Bends increase stream length 1 to2 times	Channel straight; waterway channelized for a long distance
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
8. Bank Stability	<5% of bank eroded or collapsed	5 – 30% of bank with evidence of erosion	30 – 60% of bank eroding	60 – 100% of bank scarred; many active areas of erosion
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
9. Vegetative Protection	>90% of bank covered by undisturbed vegetation	70 – 90% of bank covered	50 –70% of bank covered	<50% of bank covered; disruption evident
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
10. Riparian Vegetative Zone Width	>18 meters	12 – 18 meters	6 – 12 meters	<6 meters
SCORE (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

Appendix D (ii)

Benthic Macroinvertebrate Laboratory Bench Sheet

Station ID: _____ Sample subsorted by: _____ Date: _____

Stream Name: _____ # of Grids subsorted: _____

Date Sampled: _____ Total # of subsorted insects: _____

Sampling Method: _____ Sample Identified by: _____ Date: _____

Taxa Collected:

Porifera
- Spongillidae

Flatworms
- Planariidae

Gastropoda
- Unknown

Limpets
- Ancylidae

Snails
- Lymnaeidae
- Physidae
- Planorbidae
- Hydrobiidae
- Pleuroceridae
- Viviparidae

Unionida
- Immature
- Corbiculidae
- Sphaeriidae
- Unionidae

Oligochaeta
- Unknown

Lumbriculida
- Lumbriculidae

Tubificida
- Enchytraeidae
- Naididae
- Tubificidae

Haplotaxida
- Haplotaxidae

Leeches
- Erpobdellidae
- Glossiphoniidae
- Hirudinidae
- Pisciolidae

Branchiobdellida
- Branchiobdellidae

Decapoda
- Cambaridae
- Portunidae

Shrimp
- Palaemonidae

Isopoda
- Asellidae

Amphipoda
- Crangonyctidae
- Gammaridae
- Talitridae

Water Mites
- Hydracarina

Ephemeroptera
- Immature
- Acanthometropodidae
- Ameletidae
- Baetidae
- Baetiscidae
- Behningiidae
- Caenidae
- Ephemerellidae
- Ephemeridae
- Heptageniidae
- Isonychiidae
- Leptophlebiidae

Metretopodidae
- Neoephemeridae
- Oligoneuridae
- Psuedironidae
- Polymitarcyidae
- Potamanthidae
- Siphlonuridae
- Tricorythidae

Zygoptera
- Immature
- Calopterygidae
- Coenagrionidae
- Lestidae
- Protoneuridae

Anisoptera
- Immature
- Aeshnidae
- Cordulegastridae
- Corduliidae
- Gomphidae
- Libellulidae
- Macromiidae
- Petaluridae
- Cordullidae/Libelluidae

Plecoptera
- Immature
- Capniidae
- Chloroperlidae
- Leuctridae
- Nemouridae
- Peltoperlidae
- Perlidae
- Perlodidae
- Pteronarcyidae
- Taeniopterygidae

Hemiptera
- Immature
- Belostomatidae
- Corixidae
- Gelastocoridae
- Gerridae
- Hebridae
- Hydrometridae
- Mesoveliidae
- Naucoridae
- Nepidae
- Notonectidae
- Veliidae
- Pleidae

Neuroptera
- Sisyridae

Megaloptera
- Corydalidae
- Sialidae

Trichoptera
- Immature
- Brachycentridae
- Calamoceratidae
- Glossosomatidae
- Helicopsychidae
- Hydropsychidae
- Hydroptilidae
- Lepidostomatidae
- Leptoceridae
- Limnephilidae
- Molannidae
- Odontoceridae
- Philopotamidae
- Phryganeidae
- Polycentropodidae
- Psychomyiidae
- Rhyacophilidae
- Sericostomatidae
- Uenoidae

Lepidoptera
- Unknown
- Pyralidae

Coleoptera
- Immature
- Chrysomelidae
- Curculionidae
- Dryopidae
- Dytiscidae
- Elmidae
- Gyrinidae
- Haliplidae
- Helodidae
- Helophoridae
- Hydraenidae
- Hydrochidae
- Hydrophilidae
- Limnichidae
- Noteridae
- Psephenidae
- Ptilodactylidae
- Scirtidae

Diptera
- Immature
- Athericidae
- Blephariceridae
- Canaceidae
- Ceratopogonidae
- Chaoboridae
- Chironomidae (A)
- Culicidae
- Dixidae
- Dolichopodidae
- Empididae
- Ephydridae
- Muscidae
- Nymphomyiidae
- Pelecorhynchidae
- Psychodidae
- Ptychopteridae
- Sciomyzidae
- Simuliidae
- Stratiomyidae
- Syrphidae
- Tabanidae
- Tanyderidae
- Thaumaleidae
- Tipulidae

TOTAL: _____

Use back of sheet for subsampling information

Sub-sample and Sample Reduction Sheet

Organisms found in first grid = _____ (Grid #_____)

If <30 organisms found, continue to table below.
If >30 organisms found, discard 1st grid, enter # of grids for sample reduction and continue to table below.

Sample Reduction? Y___ N ____ Number of Grids selected for reduction =_____

Grid I.D. #	# of Organisms	Grid I.D. #	# of Organisms	Grid I.D. #	# of Organisms	Grid I.D. #	# of Organisms

Total organisms = _____ Total grids = _____

For sample reduction: _____ x _____ = _____
(# of grids after reduction) (correction multiplier) (corrected # of grids from orig. sample) {A}

IF after picking, there are >121 organisms, then return picked sample to 15-30 grid tray and remove grids (per SOP) to reduce sample to 121 organisms or less. Record data below.

Total # of organisms retained = _____
Grids removed to reduce sample to 121 organisms or fewer = _____
Percentage of grids retained for sample (to total grids) = _____

_____ x _____ = _____
(# of grids from original sample {A}) (% of grids retained) (final corrected # of grids from original sample)

QA/QC Sorting Efficiency Sheet

QC Initials ___________ **SORTERS Initials** _________________ **Pass or Fail** (Circle)

#organisms originally sorted [ ] ÷ (**#organisms recovered by checker** [ ] + **#organisms originally sorted** [ ]) **X** 100 = **% sorting efficiency** [ ]

QC Initials ___________ **SORTERS Initials** _________________ **Pass or Fail** (Circle)

#organisms originally sorted [ ] ÷ (**#organisms recovered by checker** [ ] + **#organisms originally sorted** [ ]) **X** 100 = **% sorting efficiency** [ ]

QC Initials ___________ **SORTERS Initials** _________________ **Pass or Fail** (Circle)

#organisms originally sorted [ ] ÷ (**#organisms recovered by checker** [ ] + **#organisms originally sorted** [ ]) **X** 100 = **% sorting efficiency** [ ]

QC Initials ___________ **SORTERS Initials** _________________ **Pass or Fail** (Circle)

#organisms originally sorted [ ] ÷ (**#organisms recovered by checker** [ ] + **#organisms originally sorted** [ ]) **X** 100 = **% sorting efficiency** [ ]

Appendix E

Biomonitoring Visit Summary

Date:

Field personnel:

River:

Region:

Site visit by:

A. Collection Procedures for Single Habitat:

	Yes	No
1. Reach is at least 100-meters upstream of any road or bridge crossing.	☐	☐
2. Kick sampling consisted of 6 (1m) or 12 (1/2m) sampling sites.	☐	☐
3. Kicks were times according to SOP.	☐	☐
4. Sample was collected in adequate sampling area ie. riffle/run.	☐	☐
5. Collected sample was sieved and transferred to sample container according to SOP.	☐	☐
6. Collected sample was correctly preserved in a minimum 70% isopropyl alcohol.	☐	☐
7. Benthic Macroinvertebrate Field Data Sheet was filled out appropriately.	☐	☐
8. Benthic Sample replicate (if required at site) followed SOP protocol.	☐	☐
9. Sample labels filled according to SOP.	☐	☐

NOTES:

B. Collection Procedures for Multi Habitat:

	Yes	No	
1. Reach is at least 100-meters upstream of any road or bridge crossing.	☐	☐	
2. Sampling consisted of 20 jabs, each 1 m in length, followed by 2-3 sweeps.	☐	☐	
3. Kicks were times according to SOP.	☐	☐	
4. Sample was collected in adequate sampling area according to SOP, ie. different types of habitat should represent proportion of their frequency.	☐	☐	Percent Habitat _____
5. Collected sample was sieved and transferred to sample container according to SOP.	☐	☐	

1. Collected sample was correctly preserved in a minimum 70% isopropyl alcohol. ☐ ☐
7. Benthic Macroinvertebrate Field Data Sheet was filled out appropriately. ☐ ☐
8. Benthic Sample replicate (if required at site) followed SOP protocol. ☐ ☐
9. Sample labels filled according to SOP. ☐ ☐

NOTES:

C. Habitat Assessment Procedures:

	Yes	No
1. Was assessment sheet filled out according to high or low (circle one) gradient systems.	☐	☐
2. Habitat assessment was scored according to SOP.	☐	☐

NOTES:

D. Laboratory Sorting and Subsampling Procedures:

	Yes	No
1. Sample information was recorded in Log-In book according to SOP.	☐	☐
2. Sample was washed and spread evenly in Caton Grid Tray according to SOP.	☐	☐
3. Random number was used to select first grid.	☐	☐
4. Material from grid was removed according to SOP.	☐	☐
5. **ALL** macroinvertebrates were removed from grid material according to SOP.	☐	☐
6. If more than 30 organisms in first grid, SOP was followed to continue sub-sampling.	☐	☐
7. A minimum of 4 grids were picked.	☐	☐
8. The processed sample resulted in 110 organisms $\pm$ 10% (99-121).	☐	☐
9. If number 8 resulted in NO, then SOP was followed to result in 110 organisms $\pm$ 10% (99-121).	☐	☐
10. Only **aquatic** organisms were removed from sample according to SOP.	☐	☐
11. QA/QC sorting efficiency is up to date.	☐	☐
12. All sorters have been deemed "experienced" by an "experienced" sorter.	☐	☐

NOTES:

Appendix D: Nutrient Criteria Visual Assessment Field Form

Station ID: Field Crew:

Stream Name: Ecoregion:

DEQ Region: **TP Category**

Location: **TN Category**

DATE _____ Start Time _____ Finish Time _____

LATITUDE (Decimal degrees) _____ LONGITUDE (Decimal degrees) _____

Stream Physicochemical Measurements

TEMPERATURE:_____ºC CONDUCTIVITY:_____µS/cm

DISSOLVED OXYGEN:_____mg/L pH: _____

Benthic Macroinvertebrate Collection

Method used (circle one) **Single habitat** **Multi-habitat**

Riffle quality (circle one) **Good** **Marginal** **Poor** **None**

Habitats sampled	**Riffle**	**Snags**	**Banks**	**Vegetation**
# jabs	____	____	____	_____

Algae Community

Algae community growth (% of stream bottom) **Categories; 1-10; 10-40; 40-70; >70**

Type of growth	bright green	dark green	brown	black	other
Film					
Thin mat					
Thick mat					
Filamentous					

Vascular Plant Growth

Vascular plant growth (% of stream bottom) **Categories; 1-10; 10-40; 40-70; >70**

Submerged macrophytes	
Emergent macrophytes	
Other	

Observations

Stream substrate type **Categories; 1-10; 10-40; 40-70; >70**

sand	**gravel**	**cobble**	**bedrock**	**mud**
_____	_____	_____	_____	_____

Estimated average stream width (Meters): _____

Estimated average stream depth (Meters): _____

Stream shading: (circle one) **full shade** **partial shade** **full sun**

Stream flow (circle one) **Low** **Normal** **Above Normal**

Estimated stream velocity (Meters/sec): _____

Days since last potentially scouring rain: _____

Photo documentation taken? **YES / NO**

BPJ based on observations of algae and macrophyte biomass; probability of impairment to macroinvertebrate community (circle one)

Low **Medium** **High**

Provide a brief explanation for rating: _____

_____

Watershed features

Land Use

(Indicate the predominant surrounding land use with a "1". If applicable, indicate a secondary land use with a "2".)

___ Forest ___Commercial

___Field/Pasture ___Industrial

___Agricultural ___ Residential

___Livestock ___ Other _____

Local Watershed Pollution (circle one)

No evidence Some potential sources

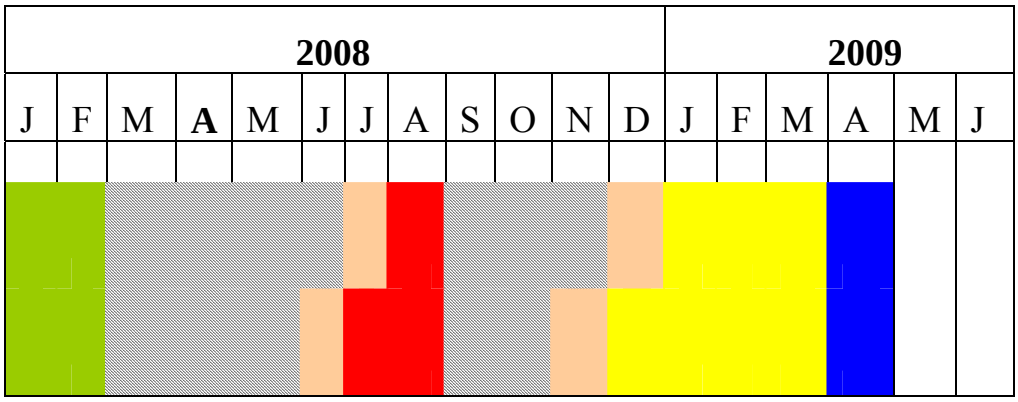
Obvious sources

Local Watershed Erosion (circle one)

None Moderate

Low Heavy

Appendix E: Timeline for Pilot Weight of Evidence Screening Value Approach to Nutrient Criteria Development for VA Wadeable Streams



Select Stations, Design Visual Assessment Procedures & Survey Forms

DEQ Biologists Collect Samples, Conduct Visual & Benthic Macroinvertebrate Assessments

DEQ Submit Spring Data to AAC

AAC Review Data, Meet with Biologists & Recommend Mid-Course Corrections

DEQ Biologists Collect Samples, Conduct Visual & Benthic Macroinvertebrate Assessments

DEQ Submit Fall Data to AAC

AAC Review Data & Recommend Final Version of the Screening Protocol

Submission to EPA

Information Transfer Program Introduction

Information Transfer Program

The VWRRC supports timely dissemination of science−based information to policy and decision−making bodies and citizens. The VWRRC used its 104 funds to support expert personnel with responsibilities related to the VWRRC's outreach and collaborative programs. The 104 funds supported:

1. Preparation of the newsletter Virginia Water Central

2. Service Training for Environmental Progress (STEP) [an educational/outreach internship program]

3. Partial support for organizing the annual Virginia Water Research Symposium

4. Partial administrative support for the Virginia Water Monitoring Council

5. Partial support for management of the VWRRC webpage

Information Dissemination

Basic Information

Title:	Information Dissemination
Project Number:	2006VA97B
Start Date:	3/1/2006
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	9th
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Stephen H. Schoenholtz

Publication

1. ***THESIS AND DISSERTATIONS***

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   Constance A. Sullivan. 2007. Biomarker responses in fathead minnows (Pimelphales promelas) during exposure to Exceptional Quality biosolids. M.S. Thesis. The College of William and Mary.
2. ***JOURNAL ARTICLES***

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Schwartz, BF, Schreiber ME, Orndorff, W. 2005. New applications of differential Electrical Resistivity Tomography and Time Domain Reflectometry to modeling infiltration and soil moisture in agricultural sinkholes, Tenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Austin TX, Sept 2005.

Adams, M.B., M.H. Eisenbies (presenter), W.M. Aust, J.A. Burger. 2007. Hydrologic modeling approaches to evaluate forest management effects on extreme flooding events. Dean's Forum on the Environment, Virginia Tech, Blacksburg, VA. February 26, 2007.

Eisenbies, M.H. 2007. Wetlands and flooding. Class lecture provided to Forested Wetlands Class, Virginia Tech, 2007.

Eisenbies, M.H. 2006. Silviculture and flooding. Class lecture provided to class on Forest Soils and Hydrology at Virginia Tech. Fall Semester, 2006

Sullivan, C. 2007. Biomarker responses in fathead minnow exposed to biosolids. Pacific Northwest Chapter of the Society of Environmental Toxicology and Chemistry. Port Townsend WA April 12−14 2007.

4. ***VWRRC SPECIAL REPORTS***

   SR33−2007: Report of the Academic Advisory Committee to the Virginia Department of Environmental Quality: Freshwater Nutrient Criteria for Rivers and Streams.

   SR32−2007: Pathogen Research Symposium: Pathways and Monitoring in Natural and Engineered Systems (Nov. 1, 2006, symposium report).

   SR31−2006: Analysis of Sinkhole Susceptibility and Karst Distribution in the Northern Shenandoah Valley, Virginia: Implications for Low Impact Development (LID) Site Suitability Models.

   SR30−2006: Report of the Academic Advisory Committee to the Virginia Department of Environmental Quality: Freshwater Nutrient Criteria for Rivers and Streams.

5. ***VIRGINIA WATER CENTRAL***

   Virginia Water Central, January 2007 (No. 40), 32 pp.

   Virginia Water Central, September 2006 (No. 39), 31 pp.

   Virginia Water Central, June 2006 (No. 38), 34 pp.

6. ***VIRGINIA WATER CENTRAL***

   Virginia Water Central, December 2007 (No. 43)

   Virginia Water Central, September 2007 (No. 42)

   Virginia Water Central, May 2007 (No. 41)

7. ***CONFERENCE PROCEEDINGS***

   Walker, J.L. (ed.). 2008. Proceedings of the 2006 Virginia Water Science and Technology Symposium. October 1−3, 2006. P12−2008. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia. 127 pp. http://www.vwrrc.vt.edu/proceedings.html

   Constantinescu, A. (ed.). 2008. Proceedings of the 2007 Virginia−West Virginia Water Research Symposium. November 26−30, 2007. P13−2008. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia. 355 pp. http://www.vwrrc.vt.edu/proceedings.html

Outreach and Information Transfer Accomplishments for 2007

The VWRRC website (http://www.vwrrc.vt.edu/) was completely redesigned and the content was reorganized and expanded to include daily updates of water-related news and legislation. As part of the redesign, a new logo for the VWRRC was developed.

The VWRRC published three quarterly *Virginia Water Central* newsletters during the reporting period which are posted and archived for public access on the VWRRC website and are emailed to a list serve with more than 500 addressees.

The VWRRC and WVWRI co-hosted the 2007 Virginia-West Virginia Water Research Symposium November 26-30, 2007 at Virginia Tech. The symposium theme was “Connecting Management to Aquatic Communities” and more than 170 participants attended. As part of the symposium, three workshops were held (Introduction to Fluvial Geomorphology, An Overview of the TMDL Process, and Tools for Watershed Monitoring and Assessment). Proceedings of the symposium have been published and are available on the VWRRC website (http://www.vwrrc.vt.edu/symposium2007/default.html).

The VWRRC provided information in response to requests from more than 50 citizens throughout the Commonwealth during the 2007 reporting period.

Three Service Training for Environmental Progress (STEP) student interns worked with the Dan River Basin Association, Grayson Landcare, Catawba Landcare, and the New River Watershed Roundtable to provide water quality data and reports for watershed management activities during summer 2007.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR−USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	0	0
Masters	1	0	0	0	1
Ph.D.	0	2	0	0	2
Post−Doc.	0	0	0	0	0
Total	1	2	0	0	3

Notable Awards and Achievements

Publications from Prior Years